The FlightGear Flight Simulator
History, status and future

A.R. Perry <*alex.perry@ieee.org*>
C. Olson <*curt@flightgear.org*>
http://www.flightgear.org/

Abstract

The open source flight simulator *FlightGear* is being developed through gracious contributions of source code and time by many talented people from around the globe. The main focus of this project is a desire to 'do things right', to minimize short cuts, to learn and advance knowledge and to have better toys to play with on ordinary computers.

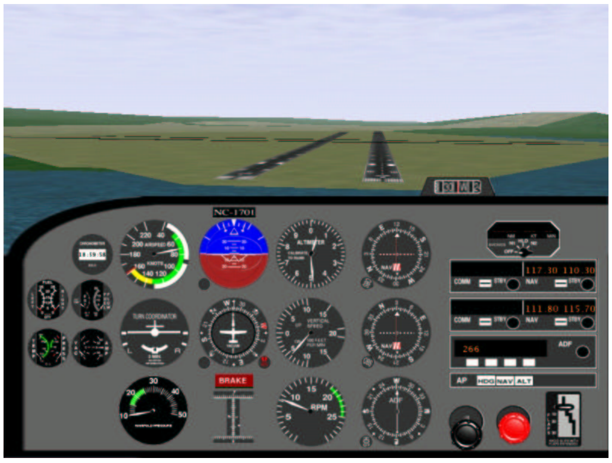

Figure 1: Cessna 172 on landing approach

In April 1996, David Murr, drawing on ideas brought forth by others, proposed a new flight simulator developed by volunteers over the Internet. This flight simulator was to be distributed free of charge via the Internet and similar networks.

Curt Olson made a multiplatform release of FlightGear[1] in July 1997. Since then, it has expanded beyond flight aerodynamics by improving graphics, adding a shaded sky with sun, moon and stars correctly drawn, automatically generated worldwide scenery, clouds and fog, head up display and instrument panel, electronic navigation systems, airports and runways, network play, and much more (as shown in figure 1).

How does it all work ?

Simulator Portability

FlightGear aims to be portable across many different processors and operating systems, as well as scale upwards from commodity computers. In addition to endianness, which inconveniences most open source projects, we must also use services (such as sound) whose implementation may be equivalent, yet very different, under the various operating systems. For those services which are common across most video games, the *PLIB* project offers a simple API that acts as a **P**ortable **Lib**rary[2]. Some aspects, such as sound support, generate libraries that implement the functionality. Other aspects, such as joystick support, are able to declare an object in a single header file and thereby avoid the library.

Compared to Windows, MacOS and Irix, the various distributions and releases of Linux-based operating systems are very similar. There are important differences, most of which cause problems when trying to build and test *PLIB*, so these rarely impact FlightGear directly. With joysticks, for example:

1. The kernel provides two methods for retrieving input data, the newer one permits more axes and buttons
2. Distributions disagree on whether the `js*` files should reside in a subdirectory under `/dev`
3. Autodetection of serial and gameport devices often occurs at boot, earlier than users expect
4. Hot-swap support for USB does not assign predictable devices, so the yoke and rudder pedals are sometimes exchanged

Once the facilities required by video games are available through the Portable Library, the remainder of the code acts as a conventional application. Compile-time incompatibilities are primarily due to `gcc` versioning and installing libraries without their header files. Run-time problems are rare, if *PLIB*'s example code was used as test cases.

Any linux user can download the source, compile it and safely expect it to run. Unfortunately, you generally cannot short-cut this process by copying someone else's binary. This is a generic problem, encountered by many applications, and led to the *Linux Standards Base* project[3].

It is made many times worse for FlightGear because hardware differences force library selections to be modified so that a given binary may not even be usable on another machine with the same Linux distribution and release if it has a different graphics card (for example). This is especially true with GL support, the extensions, and the level of GLX implementation available. This is being addressed by the *Linux OpenGL Application Binary Interface* (ABI)[4].

Simulator Structure

Current commercial PC flight simulators are proprietary, lack extensibility and thus are resistant to modification and enhancement. If the FlightGear project wishes to fill the gap, it must provide a flexible framework.

The FlightGear source tree is only one level deep, except that all the flight data models are each in their own subdirectory located under the FDM directory. Each directory contains a few header files that expose its object definitions. Other source files refer to the headers directly, without path globbing or multiple include paths for the compiler. The directory names are mostly pretty self-explanatory:

Aircraft, Airports, Autopilot, Time (in the simulated world), Cockpit, Controls (in the aircraft cockpit), FDM (only one constituent in use), GUI (menus and the like), Include (for compiler configuration), Joystick, Main (initialization and command line parsing), Network (data sharing), NetworkOLK (network play), Objects (dynamically loaded and changing scenery), Scenery (static), Weather (world wide basic factors), WeatherCM (four dimensional world database), Navaids, Ephemeris (of celestial bodies) and Sound.

In addition to the collection of interacting objects, FlightGear also exposes the high level state of the simulation in two ways. First, a meta-object *BFI* provides a long list of methods to retrieve (and, in some cases, modify) popular information that is distributed around the many different types of objects. This avoids making each source file dependent on the declarations of almost every object type and header file. These references and interactions can only really be modified at compile time.

The second exposure of the simulator state occurs through the property database, which dynamically maps a name (such as `/position/latitude`) into an object with getter and setter methods. Although slower, the dynamic access is especially appropriate for the user interface, parametric graphics elements and configuration files.

The property database is also exposed to other applications by the network interface. The command line option `--props=socket,bi,20,,5555,tcp`, for example, allows someone else (such as the flight instructor) to run `telnet localhost 5555`. This allows arbitrary properties to be viewed and modified while the simulation is running.

Many tasks within the simulator need to only run periodically. These are typically tasks that calculate values that don't change significantly in 1/60th of a second, but instead change noticeably on the order of seconds, minutes, or hours. Running these tasks every iteration would needless degrade performance. Instead, we would like to spread these out over time to minimize the impact they might have on frame rates, and minimize the chance of pauses and hesitations.

We do this using the *Periodic Event Manager and Scheduler*, which consists of two parts. The first part is simply a list of registered events along with any management information associated with that event. The second part is a run queue. When events are triggered, they are placed in the run queue. The system executes only one pending event per iteration in order to balance the load. The manager also acquires statistics about event execution such as the total time spent running this event, the quickest run, the slowest run, and the total number of times run. We can output the list of events along with these statistics in order to determine if any of them are consuming an excessive amount of time, or if there is any chance that a particular event could run slow enough to be responsible for a perceived hesitation or pause in the flow of the simulation.

Simulator Execution

Installing and running FlightGear is relatively easy under Linux, especially compared to other operating systems with weak tool automation.

1. Install Linux normally and test internet access.
2. Add video card support, using a maximum of 25% of memory for 2D display.
3. Enable hardware accelerated OpenGL support and test for speed, using *glTron*[5] for example.
4. Install *PLIB* 1.2 or above, which is already in many distributions, and test with all the supplied examples to ensure the API is working.
5. Download, compile and install *SimGear*. If your distribution already includes some components, such as *zlib*, verify that headers are present.

6. While that compiles, download the FlightGear source. Once *SimGear* is installed, start the compile and then install it
7. While the simulator is compiling, download FlightGear's base package. This contains data files that are required to execute the binary application.
8. Type `runfgfs` and enjoy.

For a computer system which is directly supported by your chosen distribution, the first five steps are often trivialized into telling the installer to ensure 'plib-dev' is present. Starting from a blank hard drive, FlightGear can be running in less than an hour.

Simulating the Pilot

The new FlightGear pilot will probably not want to remain within the San Francisco bay area, which is the small scenery patch included in the Base package. The scenery server allows the selection and retrieval of any region of the world. Joining other users in the sky is another possibility.

In a large group of users, coordinating the position and activities of all the players requires considerable network traffic, which can degrade the apparent performance. The FlightGear Deamon, `fgd`, is a standalone program which can run on a separate computer that is independent of any FlightGear session. It registers FGFS players willing to take part in a multiplayer FGFS environment via TCP/IP. Information like the player's IP/lon/lat/alt and inter-player messages can be sent to `fgd`, which in turn sends back the gathered information upon request. In this way, the simulated aircraft all become visible to each other.

Due to limited monitor size, the view that is available on a normal computer is more like the little passenger portholes on airlines and a poor substitute for the wraparound windows of general aviation aircraft. This is especially true when the simulated aircraft has an open cockpit and an unrestricted view in almost all directions.

To alleviate the problem with lack of external view, FlightGear supports synchronizing several displays together to form a panoramic or wrap around view.

FlightGear has built in support for network socket communication and the display synchronzing is built on top of this support. FlightGear also supports a null or do-nothing flight model which expects the flight model parameters to be updated somewhere else in the code. Combining these two features allows you to synchronize displays.

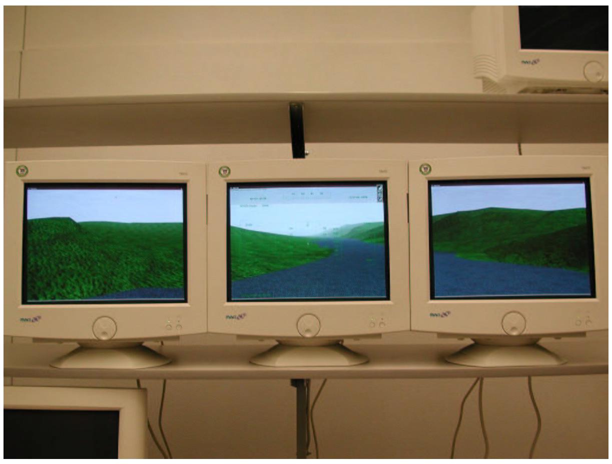
Figure 2: Panoramic scenery

For example, let's assume we want to setup the example shown in figure 2.

1. Ideally, configure three identical computers and monitors.
2. Pick one of the computers (i.e. the center channel) to be the master. The left and right will be slaves *s1* and *s2*.
3. When you start `runfgfs` on the master, use the command line options
`--native=socket,out,60,s1,5500,udp`
`--native=socket,out,60,s2,5500,udp`
respectively to specify that we are sending the "native" protocol out of a udp socket channel at 60 Hz, to a slave machine on port 5500.
4. When you start `runfgfs` on each of the slave computers, use the command line option `--native=socket,in,60,,5500,udp` to specify that we expect to receive the native protocol via a udp socket on port 5500. The second option `--fdm=external` tells the slave not to run it's own flight model math, but instead receive the values from an "external" source.
5. You need to ensure that the field of view on the scenery matches the apparent size of the monitor to the pilot. `--fov=xx.x` allows you to specify the field of view in degrees on each computer display individually.
6. `--view-offset=xx.x` allows you to specify the view offset direction in degrees. For instance,
`--view-offset=0` for the center channel,
`--view-offset=-50` for slave 1, and
`--view-offset=50` for slave 2.

There is no built in limit to the number of slaves you may have. It wouldn't be too hard to implement a full

360 degree wrap around display using 6 computers and 6 projectors, each covering 60 degree field of view on a cylindrical projection screen.

Simulating the Aircraft

The aerodynamic simulation may be only one constituent of the whole environment being simulated for the user, but its performance is critical to the quality of the user's simulation experience. Errors in this *Flight Dynamics Model* (FDM) are distracting to the pilot. Other simulator components, such as the autopilot, are designed to expect a realistic aircraft, may respond incorrectly as a result of FDM errors and provide additional pilot distractions. These factors can ruin the immersive experience that the user is seeking.

As a result of this concern, FlightGear abstracts all of the code that implements an FDM behind an object oriented interface. As future applications find that existing FDM choices do not meet their requirements, additional FDM code can be added to the project without impacting the consistent performance of existing applications.

The original FDM was LaRCsim, which models a Cessna 172 using dedicated C source that has the necessary coefficients hard coded. It is sufficient for most flight situations that a passenger would choose to experience in a real aircraft. Unusual maneuvers that are often intentionally performed for training purposes are poorly modelled, including deep stalls, incipient and developed spins and steep turns. The code also supports a Navion and a Cherokee, to a similar quality.

A research group at the University of Illinois created a derivative of LaRCsim, with simplified the models such that they are only really useful for cruise flight regimes. They enhanced the code with a parametric capability, such that a configuration file could be selected at simulation start to determine how the aircraft will fly. Their use for this modification was to investigate the effect on aircraft handling of progressive accumulations of ice.

Another group is developing a completely parametric FDM code base, where all the information is retrieved from XML format files. Their JSBSim project[6] can run independently of a full environmental simulation, to examine aerodynamic handling and other behavior. An abstraction layer links the object environment of FlightGear to the object collection of JSBSim to provide an integrated system. Currently, this FDM supports the Cessna 172 and the X-15 (a hypersonic rocket propelled research vehicle), providing the contrast between an aircraft used for teaching new student pilots and an aircraft that could only be flown by highly trained test pilots.

Figure 3: Tux flying over Woods Hole

The rest of FlightGear's configuration files are also moving towards XML, such as the engine models, the instrument panel layouts and instrument design, the HUD layout, the user preferences and saved state. The real benefit of using XML here is that people with no software development experience can easily and effectively contribute. Pilots, instructors, maintenance technicians and researchers all have in-depth technical knowledge of how an aircraft and hence the simulator should behave, so it is critical that we allow them direct access to the internals.

Both the head up display (HUD) and the instrument panel allow the user to specify an XML file describing which instruments are to be displayed and where they should be located on-screen. Individual instruments are defined in independent XML files, selecting graphic elements, texture bitmaps and transforms that modify these to build the desired effect. Some of the transforms are fixed and others are parametric on simulator data, so that the rotation angle of a needle bitmap on the airspeed instrument is determined by the computed airspeed value inside the FDM section of the simulator.

The head up display of a real aircraft uses computer generated graphics, so the software can generally detect, and correct for, the flaws and inaccuracies in the sensors that are feeding it data. As a result, the information presented to the pilot is generally accurate. Simulating that is relatively easy, since the actual state of the aircraft can be retrieved and directly displayed.

An important aspect of learning to fly an aircraft (without computer assistance) is understanding what the limitations and errors of the various instruments are, and when their indications can be trusted as useful flight data. Unfortunately, the information from panel instruments has errors, which in general only read a single sensor value with negligible correction for the limitations of the sensors being used. When the FlightGear panel advanced from no errors to having only two of the limitations implemented, the non-pilot developers went from trivially flying instrument approaches to frequent ground impacts.

Considerable effort is needed to write this code. Gyroscopes can slow down and wobble, their rotation axis can drift, they can hit gimbal stops and tumble and their power source can be weak or fail. Air-based instruments are wrong in certain weather conditions, tend not to respond immediately, can be blocked by rainwater in the lines, or become unusable when iced over. Radio navigation is subject to line-of-sight, signals bounce off hills and bend near lake shores or where another aircraft is in the way and distant stations can interfere. Still more errors are associated with the magnetic compass, and other instruments that seem 'trivial'.

Currently, the communication radios are not implemented, so that pilots cannot use their microphone inputs to interact. Radio usage is a large part of the complexity in operating at large and busy airports. Unfortunately, this often encourages pilots to fly the microphone and forget about the airplane, occasionally with disastrous results. We hope to implement this feature soon, to provide another source of challenging distractions to the pilot.

Simulating the World

The purpose of the TerraGear project[7] is to develop open-source tools and rendering libraries and collect free data for building 3D representations (or maps) of the earth for use in real time rendering projects. There is much freely available *Geographic Information System* (GIS) data on the internet. Because the core data for FlightGear has to be unrestricted, the default use of the project only uses source data that doesn't impose restrictions on derivative works. Three categories of data are used.

Digital Elevation Model (DEM) data is typically a set of elevation points on a regular grid. Currently, 30 arcsecond (about $1\,km = 0.6\,mi$) data for the whole world, and 3 arcsecond (about $100\,m = 300\,ft$) data for the United States, is available from the USGS, but better data sources are hoped for. An optimizing algorithm seeks to find the smallest number of flat triangles that provide a fairly smooth and realistic terrain contour. This algorithm reduces the number of triangles need to render an area while preserving all the detail within some specified error tolerance.

Other more specialized data such as airport beacon, lighthouse locations, radio transmission towers and the like are available in listings from various government agencies. These generally provide a short text description of the item and its geographic coordinates. The challenge is to convert each entry into a realistic visual object which can be inserted into the scenery database.

Polygonal data such as landmass outlines, lakes, islands, ponds, urban areas, glaciers, land use and vegetation are available from the USGS and other sources. The GSHHS database provides a highly detailed and accurate global land mass data so we can model precise coast lines for the entire world. Based on the source of the data and factoring in the land use data, we can select an appropriate texture which will be painted onto the individual triangles. Where necessary, triangles are subdivided to get the effect correct. Runways and taxiways are generated by converting the list of runway segments into polygons, painted with appropriate surface texture and markings, and then integrated into the scenery in the same way.

Clearly, someone can gain access to data sources that are under more restrictive licenses, use the TerraGear project tools to generate enhanced scenery and then distribute those files as they choose. Both the FlightGear and TerraGear projects encourage this kind of enhancement, because the basic open source packages cannot do this.

There is a trade-off between the quality of the scenery and the speed at which it can be rendered by the graphics card. As cards get faster, it becomes feasible to place more detail into the scenery while maintaining a useful and smooth visual effect. There are many techniques for adjusting the level of detail according to the altitude and attitude of the aircraft, to optimize the visual quality, but none of them are currently implemented as they cause visual artifacts.

Currently, the visual effect is clearly synthetic, as can be seen in figure 3, but it has sufficient information to readily permit navigation by pilotage (i.e. comparing the view out of the window to a chart). The compressed data requires about one kilobyte per square kilometer. All the information inside the scenery database is arranged in a four-level hierarchy, where each level changes scale by a factor between 10 and 100:

1. One planet, currently only the Earth
2. $10^o \times 10^o$ rectangle as shown in figure 4,
3. $1^o \times 1^o \approx 70\,mi \times 50\,mi = 100\,km \times 60\,km$,
4. $50\,mi^2 = 100\,km^2$ approximately.

One of the difficulties facing the TerraGear developers is that most information sources are only generated at a national level. It is easy to justify writing special code to read and process data files for the largest ten countries, since they cover most of the land surface of the planet,

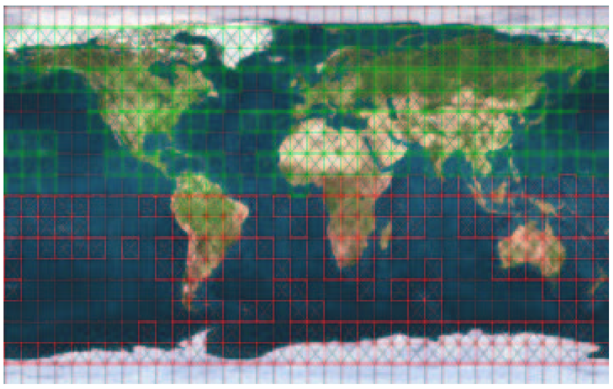

Figure 4: World scenery

but this approach rapidly reaches the point of diminishing returns.

There are already many organizations that painstakingly collect and transform the data into standardized formats, precisely for these kinds of applications. However, the huge amount of effort involved requires them to keep the prices extremely high in order to fund the conversions. Therefore, in the medium term, it is possible that these organizations (or one of their licensees) may start selling TerraGear compatible scenery files that is derived from their data archive. You can expect a high price tag for such reliable data though.

Data that is released into the public domain is generally of reduced quality, or out of date, or does not give widespread area coverage. The scenery generated from such data is actually wrong, compared to the real world, but generally only in ways that are visually unobtrusive. These errors are more visible in electronic navigation, such as needed for instrument flight, since the route tolerances are extremely tight. Navigating the simulated aircraft around imperfect scenery according to current Jeppesen (or NOS, etc) charts can be extremely frustrating and occasionally impossible when a piece of scenery is in the way.

To avoid the frustration, the *Atlas* project[8] has developed software which automatically synthesizes aviation style charts from the actual scenery files and databases being used by FlightGear. Thse charts, while inaccurate to the real world and therefore useless for flight in an aircraft, are extremely accurate for the simulated world in which the FlightGear aircraft operate. Thus, it is often easier to make printouts from the `Map` program of the *Atlas* project.

The project also includes the namesake *Atlas* application. This can be used for browsing those maps and can also connect directly to FlightGear in order to display aircraft current location on a moving map display. This capability must be used selectively by the simulator pilot, since most small aircraft do not contain GPS units with

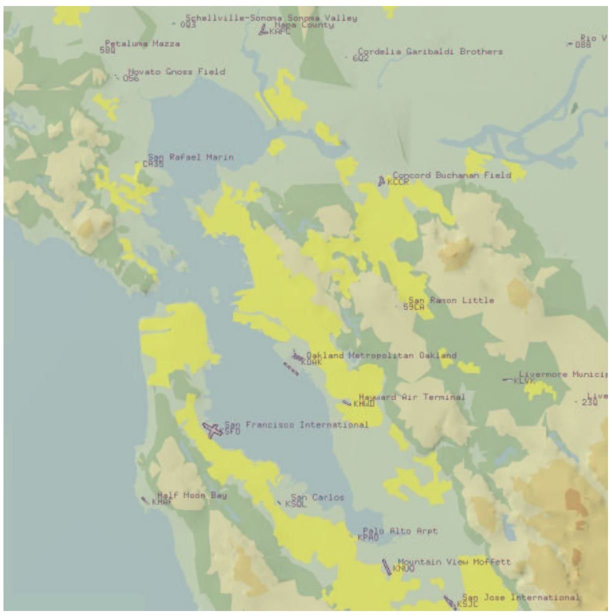

Figure 5: Chart of San Diego, California

integrated moving map displays ... yet. However, the moving map is invaluable to instructors for gauging student performance.

The connection between FlightGear and Atlas is a special case of their general capabilities. FlightGear can emit a stream of NMEA compliant position reports (the format used by GPS units) to serial port or UDP socket. Atlas can receive NMEA format position data and adjust the moving map image. The user who is browsing the chart atlas can zoom in and out, toggle the display of airports, navigational stations, terrain tint and name overlays.

Simulator Status

We have a wide range of people interested and participating in this project. This is truly a global effort with contributors from just about every continent. Interests range from building a realistic home simulator out old airplane parts, to university research and instructional use, to simply having a viable alternative to commercial PC simulators. Here are some current uses:

1. University of Illinois at Urbana Champaign. FlightGear is providing a platform for icing research for the Smart Icing Systems Project.
2. Simon Fraser University, British Columbia Canada. Portions of FlightGear were used in simulation to develop the needed control algorithms for an autonomous aerial vehicle.
3. Iowa State University. A senior project intended to retrofit some older sim hardware with FlightGear based software.

4. University of Minnesota - Human Factors Research Lab. FlightGear brings new life to an old Agwagon single seat, single engine simulator.

5. Aeronautical Development Agency, Bangalore India. FlightGear is used as as the image generator for a flight simulation facility for piloted evaluation of ski-jump launch and arrested recovery of a fighter aircraft from an aircraft carrier.

6. Veridian Engineering Division, Buffalo, NY. FlightGear is used for the scenery and out-the-window view for the Genesis 3000 flight simulator.

Reselling open source software has not been a good revenue source for other companies, partly because of the rapid version changes and partly because of the low cost of bandwidth for the consumer. Yet, several organizations are also considering making retail versions. Can FlightGear be a viable profit center?

Suppose we separate the database of visual scenery from everything else. That everything else is only few megabytes, which easily fits into a corner of a CD and will readily be downloaded whenever a new version becomes available. As with many other GUI packages, it will probably be repackaged by the distributions to ensure a painless installation for the community. There appears to be little benefit in making a product here, especially since closed source flight simulator games are available at under $\$20$.

In contrast, the scenery is more than a gigabyte for each continent, is unlikely to get any smaller, and represents a significant download. The scenery is relatively stable over time, old versions are usually useful with newer releases of the binary software, and the upgrades only add detail to an existing and viable database. There is clearly an opportunity to retail a DVD (or a dozen CDs) that contain the scenery. The marginal cost of adding a few dozen binaries, for popular operating system distributions and driver combinations, is probably trivial. Thus, this retail package is likely to be fully functional.

Alternatively, suppose we consider the pilot's viewpoint. Most general aviation aircraft cruise at below 200 knots and flight visibility is (in real life) usually below 20 miles for the lower altitudes that are accessible with ordinary non-turbocharged piston engines. Even when flying in a straight line, a maximum of 8000 square miles of new terrain will come into view during each hour of flight. Currently, the database uses about one megabyte for 600 square miles, so a streaming rate of 12 megabytes/hour will be sufficient. The rate will be lower when previously-downloaded scenery is in view.

This need not impact the core FlightGear source code. The latitude and longitude of the aircraft are already exported for use by independent programs, so the center of interest is trivially available. Since the scenery is stored in $100\,km^2$ pieces, an independent program need only generate a list of the closest elements that have not been fetched yet, and issue a `wget` to ensure that they will be available before the aircraft gets close enough for the pilot to see them.

A 56K modem is capable of 12 megabytes per hour before compression. If streaming scenery can be delivered essentially through any internet connection, it might remove the market need for retail scenery packages. Multiplying this bandwidth by a worldwide community of users will result in a sizeable traffic impact on the distributing servers. Is the total still going to be low enough to be supported for goodwill, or will free servers gradually transition to monthly access fees and maybe even deliver proprietary content?

Simulating Flight Training

FlightGear could also be helpful when learning to fly aircraft. Flight training is carefully regulated by the government, to ensure that aircraft generally stay in the sky until their pilot intends for them to come down safely. There are thus some real concerns which need to be addressed before authorities can approve a system.

1. Do the controls feel, and operate, sufficiently like the ones in the aircraft that a pilot can use them without confusion? Are they easier to use and/or do they obscure dangerous real-life effects?

2. Does the software provide a forward view that is representative for the desired training environment?

3. Are the instruments drawn such that a pilot can easily read and interpret them as usual? Do they have the systematic errors that often cause accidents?

4. Can all needed cockpit switches and knobs be operated intuitively?

5. When operated in the limited envelope of flight configurations that is applied to the training activity, does it match the manufacturer's data for the aircraft performance?

6. Are the weather settings accessible and intuitive to the instructor? How about causing system failures and broken instrumentation?

7. Can the pilot conduct normal interactions with air traffic control? Can the instructor easily determine whether the pilot is complying with the control instructions and record errors for subsequent review?

8. Is the pilot's manual for the simulator similar and arrangement to that of an aircraft, such that it can readily be used in flight?

9. Can all maneuvers be performed in the same way as in an aircraft?

In that (partial) list of concerns, the quality of the actual flight simulation (which is really what FlightGear is offering) is a minor topic and and acceptable performance is easily achieved. In contrast, a large package of documentation must be added to the software to explain and teach people how to use it correctly. This has led to a separate project `FGATD`[9], whose goal is to initially meet the lowest standard created by the United States Federal Aviation Administration (FAA). Don't expect it to finish soon.

It is easy to suggest that the FAA is being unrealistic in requiring this documentation, but they are responding to important traits in human nature that won't go away just because they're inconvenient.

For example, the things learnt first leave an almost unshakeable impression and, at times of severe stress, will over-rule later training. Thus, any false impressions that are learned by a beginning student through using a simulator will tend to remain hidden until a dangerous and potentially lethal situation is encountered, at which time the pilot may react wrongly and die. Pilots who use a simulator on an ongoing basis to hone their skills will get an excessively optimistic opinion of their skills, if the simulator is too easy to fly or does not exhibit common flaws. As a result, they will willingly fly into situations that are in practice beyond their skill proficiency and be at risk.

Clearly, a flight simulator (such as FlightGear) can only safely be used for training when under the supervision of a qualified instructor, who can judge whether the learning experience is beneficial. The documentation materials are essential to supporting that role.

What's in the future?

As with any Open Source project, there are as many possible futures as there are users and developers of the code. Some areas to think about are:

The aerodynamic models are not (yet) accurate enough for use in all flight situations, so they don't reflect the challenges and excitement of acrobatic maneuvering. The models also don't react like a Cessna 172, which is not designed or certified for such maneuvers.

Surround projectors, head mounted displays, directional sound and cockpit motion are rapidly converging into consumer technologies. Maybe we can immerse the users so well that they fly conservatively because they forget that they're not in real danger.

Recent radar and visual satellite surveys of the earth's surface have enough detail to be directly used as photorealistic scenery. But not until someone figures out how to manipulate terabytes in real time, since the data volume is about a million times larger than now.

The aircraft wake is invisible, can last five minutes, descends slowly or spreads across the ground, is blown around by the wind and is extremely dangerous to following aircraft. A future extension to `fgd` could keep track of the hundreds of miles of wake trails in a given area and notify individual aircraft when they are encountering invisible severe turbulence.

Replication and scalability is only starting to take hold in the desktop environment. A room of several hundred computers acting as X terminals for word processing can reboot and, within a couple of minutes, all be running FlightGear identically. They're ready for the next class of student pilots.

Conclusions

On the surface, FlightGear is a simple Open Source project that builds on many existing projects in the community traditions. Due to the subject it addresses, many issues and concerns are raised that rarely inconvenience most other project teams. These elements are providing the exciting challenges and variety of associated activities that the developer team is enjoying.

References

[1] `http://www.flightgear.org/`
[2] `http://plib.sourceforge.net/`
[3] `http://www.linuxbase.org/`
[4] `http://oss.sgi.com/projects/ogl-sample/ABI/`
[5] `http://www.gltron.org/`
[6] `http://jsbsim.sourceforge.net/`
[7] `http://www.terragear.org/`
[8] `http://atlas.sourceforge.net/`
[9] `http://fgatd.sourceforge.net/`

About the authors:

Alexander Perry holds M.A. and Ph.D. degrees in engineering from Cambridge University in England and currently works as a senior research engineer for *Quantum Magnetics* in San Diego. He is one of the *FlightGear* developers, a commercial and instrument rated pilot, ground instructor and an aviation safety counselor in San Diego and Imperial counties of California.

Curtis Olson holds a M.S. degree in computer science from the University of Minnesota. He currently works as a simulation engineer at the Human Factors Research Lab of the University of Minnesota developing and support their research driving simulators. He is the *FlightGear* project leader and also a major developer.