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The use of Flight Simulators for Airspace Design in Engineering Education*

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To facilitate the safe, orderly and expeditious flight of aircraft from one airport to another, airspace structures, such as airways, departure and arrival instrumental flight procedures and holding patterns, are defined in the airspace. The criteria and principles of Airspace and procedures are part of the syllabus of the Aeronautical Engineering degree at the Escuela Universitaria de Ingeniería Técnica Aeronautica (EUITA) [University School of Aeronautical Technical Engineering] of the Universidad Politecnica de Madrid [Polytechnic University of Madrid]. To help students to master the theory and practice required, a specific course, in the latter stages of the degree, is devoted to this discipline. The course includes both a theoretical part, in which the principles behind the standards are introduced and explained, and a practical part where the theory is applied. This final part consists of two main activities: firstly, the students design the procedures, and secondly, these use these same procedures to fly, on a low cost flight simulator cockpit, under teaching staff supervision. In this students can see the results of their work and better assimilate the design principles. The flight simulator has been specifically developed for this purpose by professors of the Infrastructure, Aerospace Systems and Airport Department, and is based on a commercial 'off the shelf' flight simulation videogame, called X-plane. The professors have also created a complete practice program on the simulator, so that the student can better understand how instrumental flight procedures impact on aircraft operation.

Keywords: Videogame; flight simulator; airspace structures; flight instrument procedures; aeronautics; engineering

1. Introduction

An Air Navigation System encompasses all the infrastructure, technical and human resources required such that that an aircraft can define its trajectory and fly safely and expeditiously from its origin to its destination [1]. To facilitate the orderly movement of the aircraft, airspace routes, airways, instrument flight procedures and others airspace structures must be defined. The design of these procedures is a critical element for the safety of aircraft operation, as these procedures ensure aircraft separation from the terrain, and contribute to ensuring aircraft separation once in the air. Their proper planning and design can be effective in reducing the likelihood of aircraft accidents or incidents. The converse is also true: poorly designed airspace can create situations where accidents or incidents are more likely to occur [2].

Airspace and procedure design should follow the principles laid down in ICAO Annex 6 'Aircraft Operation' [3], ICAO Doc 8168 (PANS-OPS) [4] and Doc 4444 (PANS-ATM) [5]. PANS-OPS provide criteria for the design of procedures covering instrument arrival, holding, approach and departure. PANS-OPS provisions also cover en-route procedures where obstacle clearance is a consideration. PANS-ATM provides procedures for air navigation services, whose basic tenets form the basis of airspace design. The EUROCONTROL Manual for Airspace Planning also provides guidance material for airspace [6]. This is supplemented by Guidance Material for the design of Terminal Procedures for Area Navigation [7].

Aeronautics engineers are actively involved in airspace design and in related activities. Instrument Flight Procedure Design is one of the areas that students of the EUITA Air Navigation Degree need to master [8]. According to ICAO [9], Flight Procedure Designer Training must be competency based. This is a fundamental difference with respect to traditional education. Traditional education is centered on the teacher and the unit of progression is time. Whereas in competency based education teaching is centered on the student and the unit of progression is the mastery of the skills [10–13]. Mastering that discipline not only requires a broad technical knowledge (procedure designers need to know topics such as geodetics and mapping, FMS database coding, aircraft performance, EUR-OPS and noise modeling), but also an in depth understanding of aircraft flight (principles of flight) and a certain intuition in order to understand and anticipate the impact of the procedures on aircraft operation.

Being conscious of the fact that in engineering education one of the basic problems is how to put into practice the theoretical knowledge gained in engineering courses [14], at EUITA an innovative project has been developed to help the students to

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master this area. A specific course in the later stages of the Aeronautics Degree is devoted to this discipline. The course includes a theoretical part devoted to the principles behind the standards, and a practical part. In the practical part the students master the practical abilities required by designing themselves instrumental flight procedures and developing the sensitivity required by flying these procedures on a low cost flight simulator. That way, the student can see the results of their work, and can check the impact of their procedures on aircraft operation.

The innovative component of the project lies in the use of a commercial 'off the shelf' flight videogame simulator to recreate the virtually real environment of an aircraft cockpit in which real learning can take place. Moreover, the course professors have developed a complete set of educational simulations, centered on the students and the learning process. These educational simulations are at the same time instructive, motivating and fun.

2. Educational simulations for the design of airspace structures and instrument flight procedures

Every aircraft that flies follows a similar flight pattern that begins before take-off and ends after landing. This pattern is called a flight profile. A typical commercial flight profile has seven phases as indicted in Fig. 1.

In each phase of a typical flight the pilot must follow a specified procedure that provides course guidance and obstacle separation, based upon a series of predetermined maneuvers supported by flight instruments. For example, in the arrival phase at the destination airport Instrument Approach Procedures (IAPs) are defined and published on an Instrument Approach Chart (IAC) as shown on the left hand side of Fig. 2.

Instrument approaches are generally designed so that the pilot of an aircraft in Instrument Meteorological Conditions (IMC), by the means of radio navigation aids and with no assistance from air traffic control, can navigate to the airport, hold in the vicinity of the airport if required, then fly to a position from where the pilot can obtain sufficient visual reference of the runway for a safe landing to be made, or execute a missed approach if the visibility is below the minimums required to execute a safe landing. The total procedure comprises a maximum of 5 different segments and may include a holding pattern (see right hand side of Fig. 2).

- Arrival: where the pilot navigates from the last en-route point to the Initial Approach Fix (IAF) and where holding can take place.
- Initial Approach Segment: the segment of an instrument approach procedure between the Initial Approach Fix (IAF) and the Intermediate Fix (IF) or, where applicable, the Final Approach Fix (FAF) or Point (FAP).
- Intermediate Approach Segment. That segment of an instrument approach procedure between either the Intermediate Fix (IF) and the Final Approach Fix (FAF) or Point (FAP), or between the end of a reversal, racetrack or dead reckoning track procedure and the final approach fix or point, as appropriate.
- Final Approach Segment: That segment of an instrument approach procedure in which alignment and descent for landing are accomplished.
- Missed Approach: The procedure to be followed if the approach cannot be continued.

In order to illustrate the didactical principles of the project described in this article, let us look at a particular element of the previously described approach procedure, the Holding Pattern. A holding pattern is a predetermined maneuver designed to keep the aircraft waiting in a zone when it is necessary to provide aircraft separation along an airway, during terminal arrival or on missed ap-

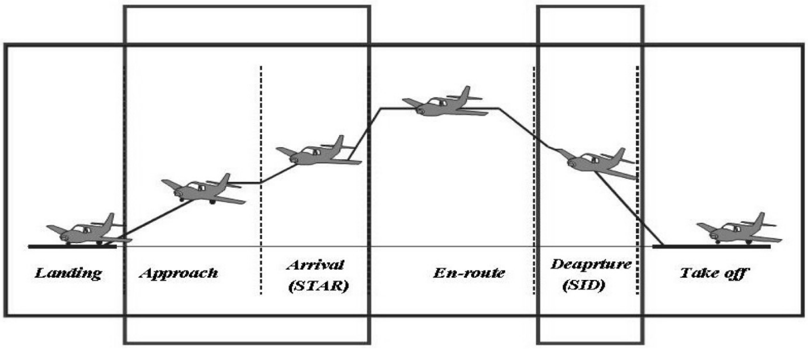

Fig. 1. Typical flight profile.

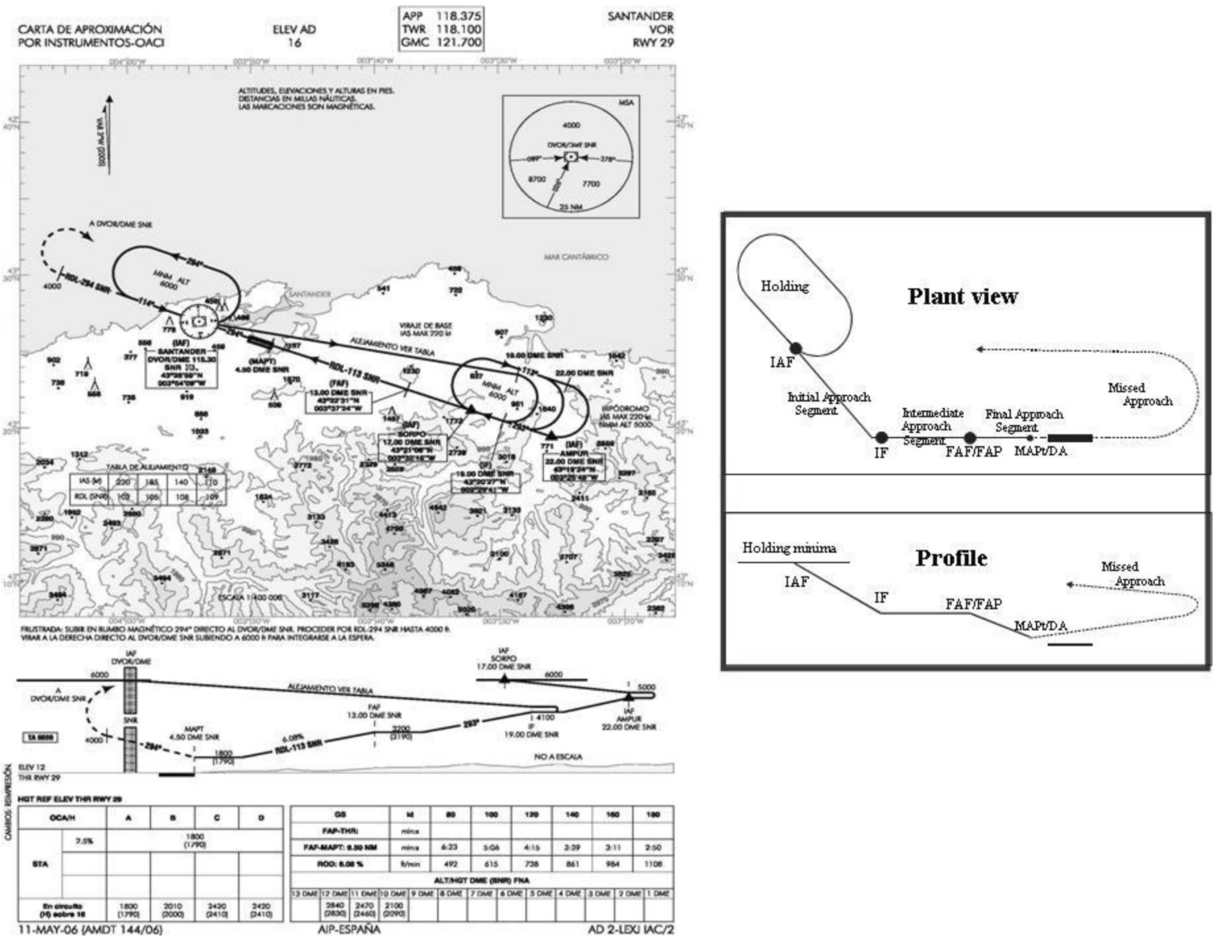

Fig. 2. Typical Instrument Approach Chart (IAC) and phases of an Instrument Approach Procedure (IAP).

proach. It provides a protected airspace for safe operation during holding. A standard holding pattern is a race track shaped course based on a holding fix. It incorporates two straight legs, named inbound and outbound legs, and two 180 degree right or left turns. The parts of the procedure are indicated in Fig. 3. The holding fix can be a radio beacon such as an NDB or VOR, it can be created using two crossing VOR radials (a so called intersection), or it can be at a specific distance from a VOR using a coupled DME.

Once a holding instruction has been issued the pilot should proceed directly to the holding fix. There are three standard types of entry: direct, parallel, and teardrop (see Fig. 3) depending on the difference in angle between the direction the

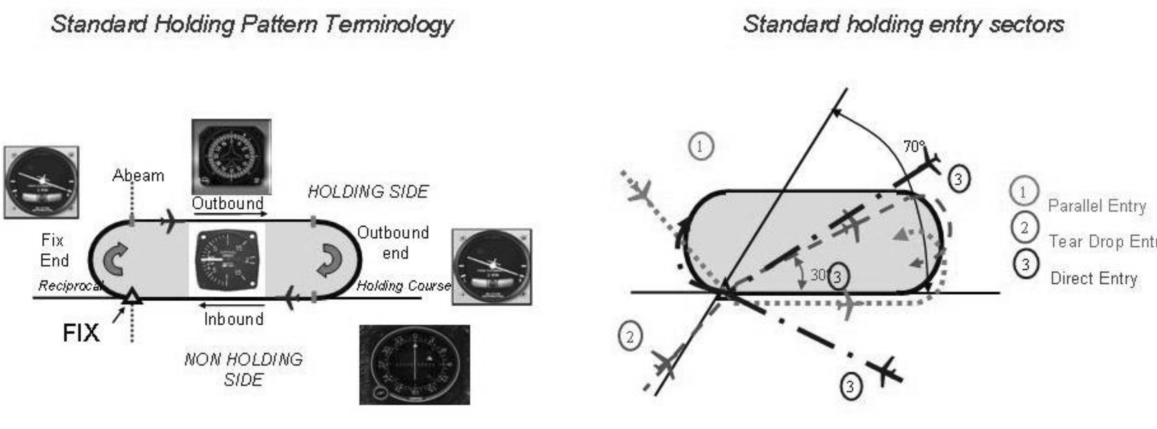

Fig. 3. Standard holding pattern and standard holding entry sectors.

aircraft flies to arrive at the beacon and the direction of the inbound leg of the holding pattern. For the sake of simplicity we will hereafter refer to the direct one, as is simple to illustrate. Upon crossing the holding fix, a turn into the outbound leg must be initiated. After that, the airplane should be flown on the outbound heading for one minute before making a right (or left) turn to intercept the inbound course. Once on the inbound course it will fly until crossing again the holding fix. At that point, the pilot may be required to continue with the approach procedure or to stay on the holding for some time. In this last case the pilot should keep repeating the predefined racetrack pattern. A standard holding pattern uses right or left hand turns and nominally takes 4 minutes to complete (one minute for each 180 degree turn, and two one-minute straight ahead sections).

As stated before a protected airspace, named holding area, should be provided to guarantee that the aircraft is not exposed to risk of collision with the terrain or with other aircraft flying close by. Protection areas for holding pattern are constructed taking into account all the factors that can cause the aircraft to deviate from the nominal holding pattern. These areas are calculated and drawn so that they:

- accommodate the fastest aircraft category;
- consider leg timing or distance;
- account for navigation accuracy values, flight technical tolerance and heading tolerance;
- consider the impact of wind and temperature

and are adjusted for the various types of entries.

Figure 4 represents a nominal holding pattern over a VOR (the nominal trajectory the aircraft is supposed to fly) surrounded by its holding protection. As can be seen, the holding area includes the basic holding area, the entry area and the buffer area. The basic holding area, at any particular level, is the airspace required at that level for a standard holding pattern based on the allowances for aircraft speed, wind effect, timing error, holding fix characteristics, etc . . . The entry area includes the airspace required to accommodate the specified entry procedure.

The design of procedures and the associated protection areas is sometimes difficult and elaborate, as it requires taking quite a lot of factors into consideration. It becomes difficult for the students to comprehend the physical reality behind all the calculations. Sometimes they become overloaded by all the details of the calculations, and so apply them in a mechanical way, losing sight of the objective.

In order to enable them understand the basic principles behind the procedures, we organize specific exercises with the flight simulator. After a theoretical explanation, the students design a complete procedure and then practice it on the simulator under different flight conditions. For example, to illustrate the main factors influencing the holding protection area and their relative importance the students are instructed to fly several holding patterns. They practice the three different entry types, holding with and without wind, and so on. The footprints of the flights are saved on the computer, and deviations from the nominal path in each case are subsequently studied. In this way, the students can check by themselves the impact of the different factors on aircraft trajectory deviation and analyze to what extent the protection area provides adequate protection.

To illustrate the analysis made by students after passing by the simulator, Fig. 5 presents the footprint of a holding pattern flown by a student without wind and the footprint of the same holding pattern flown with wind. In this case, deviation form the nominal path due to wind, that constitutes a major

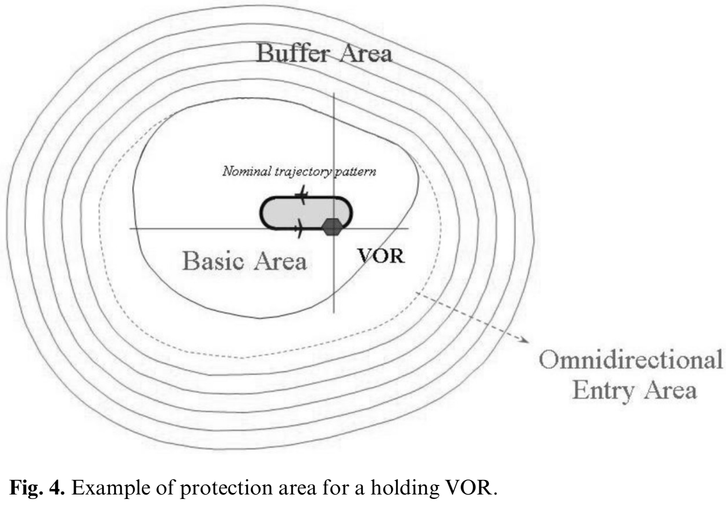

Fig. 4. Example of protection area for a holding VOR.

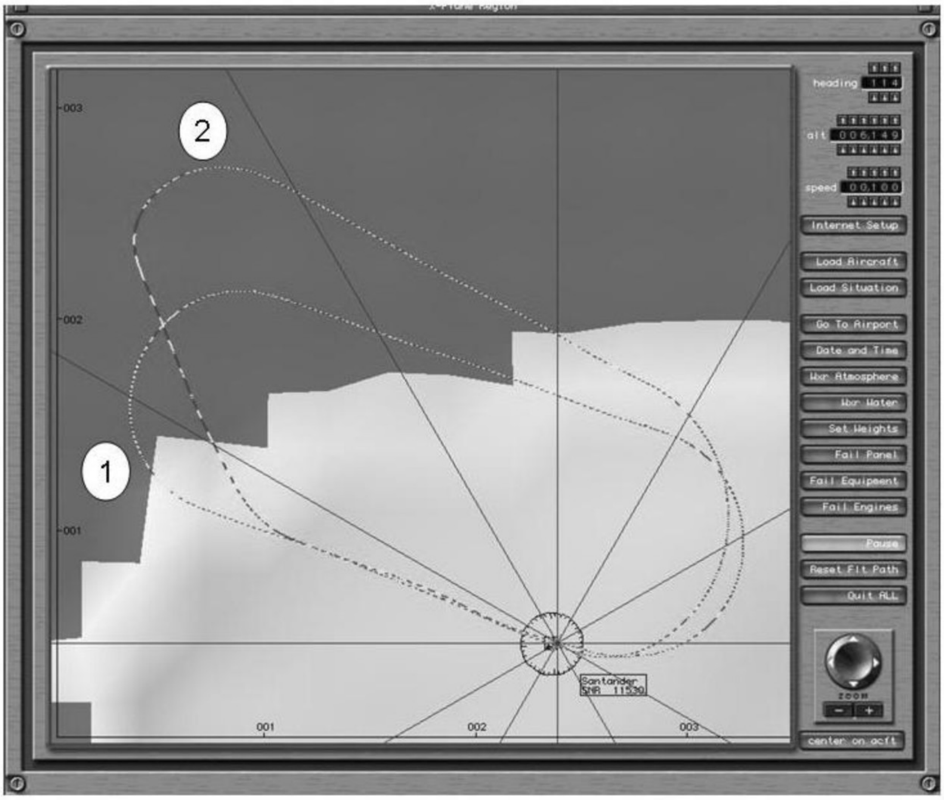

Fig. 5. Holding patterns flown by students with and without wind.

factor during holding procedures, can be easily observed. The same principles exposed for the holding pattern are applied to the design of the different segments of the instrumental procedures supporting the various phases of flight.

To illustrate the concept, Fig. 5 presents the footprint of two consecutives holding patterns flown by a student. Footprint 1 corresponds to a holding pattern flown without wind at a speed of 100Kts. As can be seen it reproduces the nominal trajectory pattern quite well. Footprint 2 is the trajectory described by the aircraft when flying the same holding, but in the presence of a 20kt wind from the south. The wind from the south causes the initial turn to deviate from the nominal as can be seen in the figure. When flying on the outbound heading the aircraft drifts to the north due to the wind and its trajectory deviates from the nominal holding pattern. The turn at the outbound end leaves the aircraft far from the inbound course. So the pilot should correct the trajectory and fly to intercept the inbound course. In this case, deviation from the nominal path due to wind, which constitutes a major factor during holding procedures, can be easily observed. The same principles used for the holding pattern are applied to the design of the different segments of the instrumental procedures supporting the various phases of flight.

3. Description of the Low Cost Flight Simulator

When most people think about flight simulators they picture the giant full-motion simulators used by the airlines. However, there are many other types of flight simulators, including commercial software packages that run on a PC. This type of simulator has been around for nearly as long as personal computers. The technology for these products has advanced considerably, allowing for a surprisingly realistic experience. As a result PC flight simulator are gaining acceptance within the aviation community for use not only as pilot training device, but also as training tool in other aeronautical disciplines such as engineering [15–17]. Fig. 6 shows the low cost simulator built for this educational experience. The simulator is based on the following off the shelf commercial products.

- Simulation Engine: X-Plane is a flight simulator for personal computers produced by Laminar Research. It runs on iPhone/iPod Touch, Palm's WebOS, Linux, Mac or Windows. X-Plane can be packaged with other software to build and customize aircraft and scenery, offering a complete flight simulation environment. X-Plane also has a plug-in architecture that allows users to create

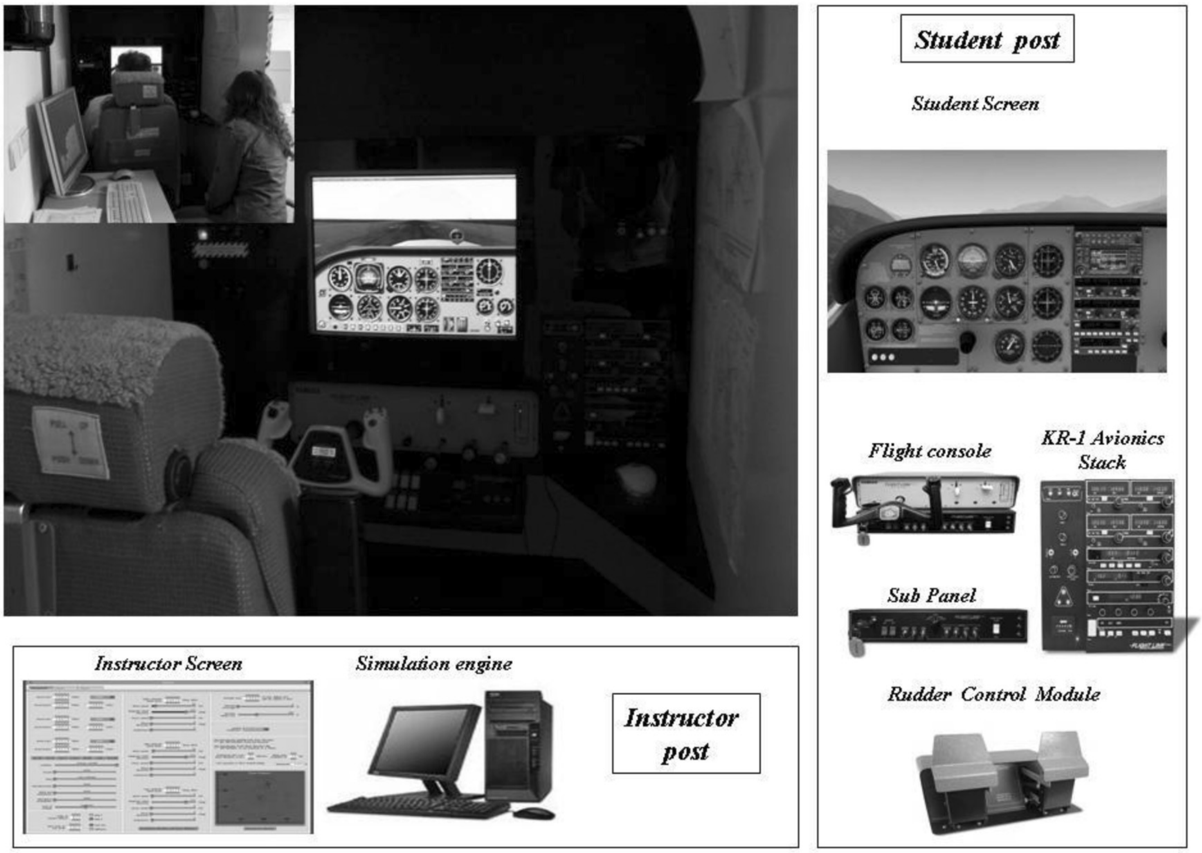

Fig. 6. Low cost simulator for educational simulations.

their own modules, extending the functionality of the software. The simulator is configured on just one PC with a dual monitor. The main screen in the cockpit shows views of the scenery for the student and the auxiliary monitor, placed at the instruction post, may be used to show the panel or map or instructor console.

- Flight console: The AV-IFR is Flight Link's 'flag ship' designed to be used for complex, high performance single engine as well as multi-engine training. Its principal features include a full size control wheel, Cessna style throttle, prop pitch and mixture control, servo-powered electric trim, heavy duty tactical feel gear and flap switches, push-to-talk and elevator trim switches on the left side of the grip AND four way view switch on the right side of the grip.
- Sub Panel: The Flight Link Sub Panel mounts on the bottom of the Flight Console and allows the pilot to control most of the systems found in all high performance single engine aircraft. Its main features are Magnetos key switch , Starter button, Master (ELEC., ALT., Avionics) rocker switches, Pitot heat rocker switch, Fuel pump rocker switch, Lights (NAV, Land, Taxi, BCN) rocker switches, Four position (off, left, both, right) fuel selector, Cowl Flaps, Three system operation buttons.
- Rudder Control Module: The Rudder Control Module (otherwise known as the RCM) uses industrial grade hydraulic cylinders which simulate accurate damping effect found while in flight.
- KR-1 Avionics Stack: It incorporates Bendix-King standard equipment for general aviation avionics. Its main features are realistic dual concentric radio knobs, orange gas plasma displays, two KX 165 NAV / COMM's, KR 87 ADF, KN 62A DME, KT 71 transponder, KFC 150 autopilot, OBS 1 & 2, altimeter and DG concentric knobs, individual marker beacon lights, full functioning red and green gear lights and HOBBS meter.

4. Elements of a successful educational simulation

We have included the three essential elements which, according to Aldrich [18], can be used to create successful educational experiences: simulation, game and pedagogical elements. Simulation elements permit discovery, experimentation, practice, and active construction of linear, systems, and cyclical content. Game elements provide familiar and entertaining interactions that drive up the time spent by the student within the educational experience. Although they do not directly support the learning objectives, they are, as Aldrich says, the 'spoonful of sugar that helps the medicine go down.' Finally the pedagogical elements are the background material that supports the content. These elements are the most important. They should drive the learning experience and organize the other elements around it.

Additionally, based on the previously described work, the following points have been identified as key issues for developing a successful educational simulation program. First of all, simulations should be real or virtually real; that means that they must simulate the core part of the activity sufficiently well enough that real learning can take place. This concept of simulating reality is key for educational purposes as introduced by Rheingold [19] in his book *Virtual Reality* where he deals with technology that ' . . . creates the completely convincing illusion that that one is immersed in a world that exists only inside a computer'. Luckily the sophistication of modern PC flight simulators is so high that the ground school portions of what is required for a beginner's pilot license can be learned on the computer.[1] In this case the PC flight simulator has been integrated in a physical mock-up of an aircraft cockpit with real instruments providing an even more realistic environment.

The second crucial element is the proper planning of the simulation exercises [20–21]. A very important factor for success is to define clear objectives for each exercise developing a clear picture and understanding of what students are expected to learn. It is useful to prepare the exercise with the student in a debriefing session where the purpose of the simulation should be clearly explained. Exercises should be designed in a way that facilitates the students becoming participants, not just listeners or observers. Exercises should also be motivators and get the student's involvement in the activity. Fortunately, current flight PC simulators are conceived as video games so the player becomes the center of the activity. Moreover, notwithstanding the complex graphics and technical performance of simulators, they are fairly easy to use even for those who have never played before. Little training on the features of the simulator is required to prepare the student to carry out the educational simulation exercises.

[1] *X-Plane* is also used in non-motion and full-motion flight simulators for flight training. Some of these implementations have been certified by the FAA for authorized flight instruction such as Flight Level Aviation and Simtrain.

The third important element is the teacher [22]. The use of simulations puts the teacher in a new role. The teacher's role in this educational experience is no longer that of a presenter of information but rather that of a guide or coach, who helps the student in the learning process. This function is the inevitable result of the evolving role of the teacher in education. With the use of this kind of simulation teachers evolve into their new role naturally. In that sense this experience is also very interesting and useful for teachers and constitutes a learning experience for them. Each successful simulation should also include a 'coaching guidance' component, to help guide the learner through the tasks and to provide advice at various levels of detail along the way. There is also a feedback component that provides the learner with information on how well he or she performed the task [23]. These new roles have to be played by the teacher in this new experience.

Preparation of the practical program took almost one academic year. It included the construction of the cockpit simulator, the HW and SW elements integration and the design, test and tuning of the exercises on the simulator. Most of the efforts were required to prepare motivating exercises that facilitates the students become participants and involve in the activity. The simulation program was integrated by two exercises, each one of two hours of duration. Very little training on the simulator was necessary in advance to prepare the student to carry out the educational simulation exercises. The only homework required was the study of the theoretical material and the reading of the exercises guidelines.

In order to evaluate the results and acceptance of this program, a survey is undertaken each year to monitor students' satisfaction with various aspects of their experience. The survey has been designed to build a picture of the students overall satisfaction and a picture of their performance improvement. The survey asks students to rank the practice program from 0 (very bad) to 5 (very good) and covers areas such as: Quality of Teaching and Learning, Quality of the simulation elements, Adequacy of the Pedagogical Elements, Background Material, Assessment and Feedback, Organisation and Management, Skills and Personal Development; as well as a question on overall satisfaction. The following items are evaluated in the Skills and Personal Development category:

- Instrument flight procedures data interpretation.
- Instrument flight procedures design.
- Instrument flight procedures flight.
- Instrument flight procedures publication.
- Use and application of standards.

In addition, all students have the opportunity to

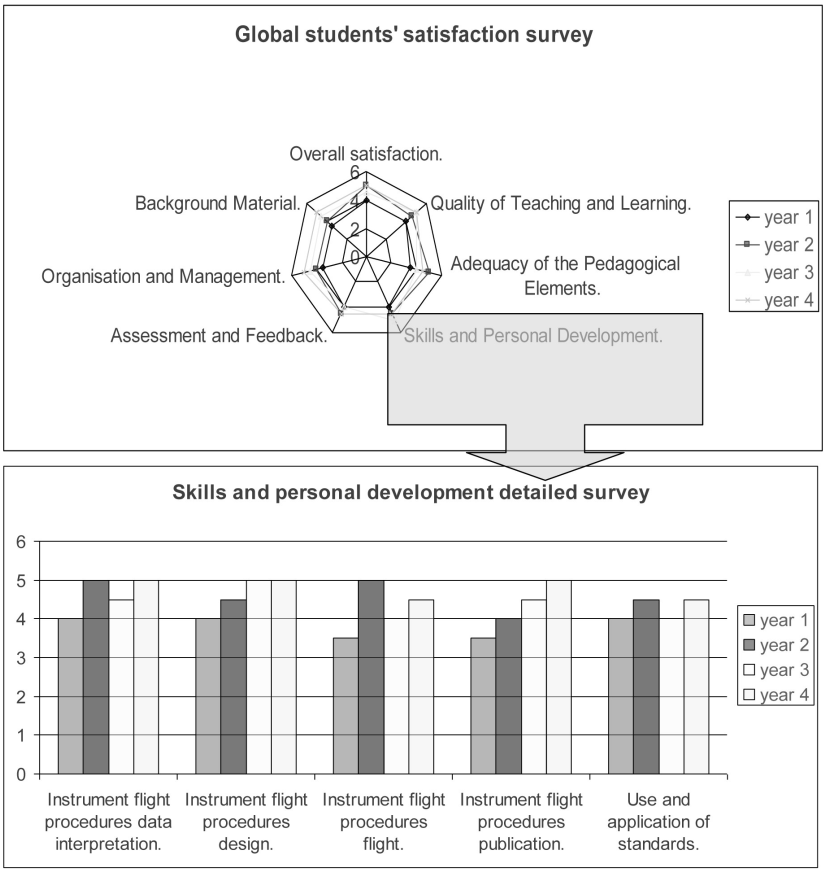

Fig. 7. Satisfaction Survey.

comment freely on particularly positive or negative aspects of their experience. Figure 7 summarizes the mean value of the results obtained on the survey during the lasts years.

Objective evaluation of the student's skill improvement was verified through the final exam. About 25% of the final exam mark was the result of a test where the student should read and interpret a Standard Instrumental Flight Procedure. An increase of two points, from six to eight, was observed in the mean value of the mark obtained by the students in this test. These results confirmed the positive impact that the virtual laboratory had in what they actually learnt.

5. Conclusions

The technology of current home PC flight simulators, specifically their powerful graphics and the simulator physics models, makes them a useful resource for training and education. Although the teacher must help the student be aware of the simulator's weak points, to avoid picking up misconceptions, PC flight simulators are being increasingly used as a training tool in aeronautical disciplines such as engineering.

One of the values of a good simulation is its ability to develop concepts and conceptualization. Properly designed educational simulations enable students to internalize major concepts. Simulations can provide effective learning; allowing learners to practice skills in a realistic environment.

Nevertheless the success of an educational simulation requires an emphasis on the educational components rather than just the simulation aspect. The goals of educational simulations must be not only to provide a practice environment, but also to provide a specific learning environment (with some type of guidance and feedback for the teacher).

A powerful educational experience focuses on the learning objectives and frames other elements around it. What to model (simulation elements) or what to reward (game elements) can not be decided until the learning objectives and the pedagogical elements themselves have been established. Additionally the use of coaching guidance and feedback, in each of the simulation-based learning programs, has to be carefully designed to suit the students and the skills being taught.

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