Flight Simulator of Light and Ultra-light Sports Aircraft

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***Abstract* — This paper provides an insight into the development and implementation of a flight simulator intended for the training of pilots of light and ultra-light sports aircraft. There are many simulators of large airliners and military aircraft in service today; however, simulators of sports airplanes are extremely rare. This can be attributed mainly to high development and production costs of such simulators. The primary aim of this project is the development of a reasonably-priced flight simulator for potential customers (sports flight schools) while maximizing simulation authenticity and accuracy. In addition to audiovisual and control systems, the simulator is equipped with modules enabling the simulation of motion effects, which can have, particularly in this type of aircraft, a significant impact on the pilot's reactions and decisions. A major part of this paper provides a description of a parallel manipulator (Stewart platform) and the options of employing it for motion simulation purposes.**

Key Words — Flight simulator, virtual reality, Stewart platform, wash-out filter, motion effects simulation, parallel manipulator

1. Introduction

This paper describes the development of a flight simulator of light and ultra-light sports aircraft.

Simulators are devices reproducing, as accurately as possible, the characteristics and behaviour of real devices such as aerospace and land vehicles. Flight simulators are typically used for pilot training and for research and development purposes.

Involving a simulator in the training process has two main benefits: First, any mistakes the pilot makes in training do not jeopardize his health. The second benefit is an economic one – it is much cheaper to operate a simulator than a real device.

There are many simulators of large airliners and military aircraft in service today; however, simulators of sports airplanes are extremely rare. This can be attributed mainly to high development and production costs of such simulators. However, rapid development of information technology and a significant price drop in recent years has made flight simulators suitable for the training of pilots of light and ultra-light aircraft as well. Flight simulators would allow future pilots to practice in safety and learn how to cope with difficult and dangerous situations – which they could never do in a real plane. In addition, simulators can decrease training costs significantly.

In the first place, any simulator intended for this purpose has to affordable for potential customers, in particular flight schools. At the same time, however, it has to be useful, i.e. provide accurate and authentic experience.

The rest of this paper describes the current status and future development of a flight simulator of a light or ultra-light aircraft designed by Pragolet, s. r. o.

2. Simulator Structure

Figure 1 shows the general block structure of the flight simulator. The centrepiece of the simulator is a mathematical model of the dynamic behaviour of the plane. The mathematical model is connected to other components via different communication interfaces. The following sections provide a description of the most important components, explaining their role in the design of the simulator of light and ultra-light aircraft.

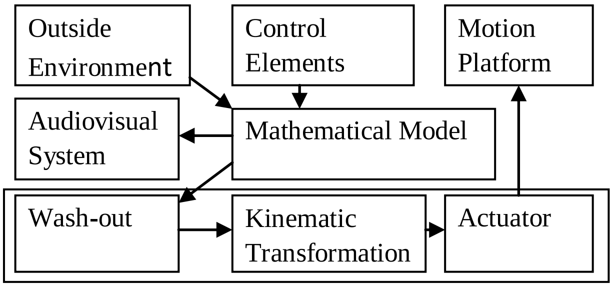

Fig. 1: Flight simulator structure.

3. Mathematical Model

The centrepiece of the simulator is a mathematical model of an airplane. The accuracy of the mathematical model determines the overall quality and authenticity of simulation. The model reads the outputs of individual control elements and calculates the values of forces and moments acting on the simulator, thus determining, taking into consideration the effects of the outside environment, the current state of the airplane (such as its position, speed, etc.).

There are two basic approaches to designing mathematical models for aircraft simulators. The first,

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more complex approach makes use of actual airplane geometry, whereas the second, more straightforward approach (at least in mathematical terms) is based on aerodynamic coefficients. Aerodynamic coefficients are figures which, after multiplied by another value (such as wing area and dynamic pressure), provide the forces and moments acting upon the aircraft.

As its main benefit, the first approach makes it possible to study aircraft behaviour under non-standard operating conditions as well. However, there is a flip side too as the model is very difficult to derive and involves difficult calculations, thus being more suitable in particular for experimental purposes.

The other approach is much more straightforward but requires aerodynamic coefficients of the airplane in question; these can either be obtained from the aircraft manufacturer or measured. In addition, the accuracy of a mathematical model using aerodynamic coefficients is limited to the scope of measured data.

The mathematical model for the flight simulator described in this paper makes use of the second approach, i.e. aerodynamic coefficients, and has been implemented in JSBSim.

JSBSim Flight Dynamics Model

JSBSim is a cross-platform open-source generic flight dynamics model written in C++ [4] and has been incorporated into many large flight simulation applications and frameworks (such as FlightGear and OpenEaagles). Aircraft data, including aerodynamic coefficients and other parameters, are stored in one or more XML files. JSBSim runs as a standalone application, communicating with its environment via standard interfaces (for instance sockets). More details of the model and its behaviour as well as the equations used for numerical calculations can be found in the documentation [4]. A theoretical analysis of these equations is provided for example in [2] or in [1].

The first release of the simulator software made use of an already existing model of the Cessna 172 Skyhawk. In future versions of the simulator, it is envisaged to introduce more aerospace vehicles, specifically other light and ultra-light aircraft frequently used in flight schools.

Figure 2 shows an extract from the flight dynamics model code of the Cessna 172 Skyhawk.

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    <version> $Id: c172p.xml,v 1.18 2007-01-1
    <description> Cessna C-172 </description>
</fileheader>

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    </location>
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        <y> 0 </y>
        <z> 48 </z>
    </location>
    <location name="VRP" unit="IN">
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        <y> 0 </y>
        <z> 38.5 </z>
    </location>
</metrics>
```

Fig. 2: Extract from the flight dynamics model code of Cessna 172.

4. Visualisation System

Visualisation systems form an integral part of modern simulators. The system generates imagery of the outside world based on the current position of the aircraft and using data from the terrain database, sending this data to the display device. Other visualisation elements are often used in addition to the central unit displaying the vicinity of the aircraft, such as systems representing the plane's control panel and/or other parts of the cockpit. In general, visualisation system elements used in flight simulators can be divided into the following categories based on their role:

- image generator and
- displaying system.

Image Generator

There are many commercial and non-commercial image generators available today, some of them designed exclusively for flight simulators. The simulator described herein makes use of the FlightGear image generator (Figure 3), the reasons for this decision being listed below:

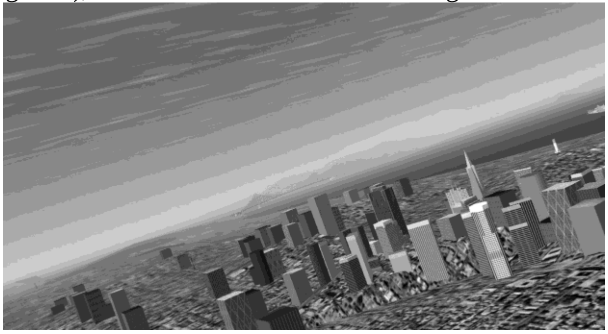

Fig. 3: FlightGear image generator.

- FlightGear is distributed as open-source under the GNU General Public License and thus can be modified in future if required.
- FlightGear is a multi-platform development project; currently, there are builds for Microsoft Windows, Linux, Mac OS and other operating systems.
- FlightGear makes use of the JSBSim flight dynamics model described in the previous section.
- FlightGear supports the MATLAB-SIMULINK development environment.

FlightGear makes use of OpenGL, the most popular programming interface for applications rendering 2D and 3D graphics. Hardware requirements are comparable to standard desktop computers. It is recommended to use a video card with a dedicated hardware accelerator (GPU) supporting the OpenGL standard.

As FlightGear is open source, its core functionality can be extended with many additional plug-ins and programmes available on the Internet, such as various editors of terrain databases and objects (buildings, bridges, etc.).

FlightGear is used for R&D purposes by many universities worldwide (Technische Hochschule Aachen, University of Illinois and many others) [10].

Displaying System

While the image generator creates objects, textures and other scenery elements, the displaying system presents this data to the pilot. Generally speaking, one of three main displaying system types can be used in flight simulators: simple projection, direct view display or direct view display with a collimator (collimated direct display). (Dual projection systems are not used very often in flight simulators.) Each displaying system type has its pros and cons and their prices are different too. The list below gives an overview of the criteria which needs to be taken into consideration when determining the most suitable displaying system type for the flight simulator described herein:

- Price: As set forth in the beginning, the price of the simulator has to be relatively low with regard to affordability for potential customers.
- Low weight and compact design: Given that it is intended to simulate motion effects as well and as the displaying system has to be placed in the cockpit of the simulator, it has to be relatively light and compact.
- View accuracy: For pilots of light or ultra-light aircraft, spatial orientation is much more important than, for example, for pilots of a large airliners cruising at high altitudes.

Given that simple projection has considerable spatial requirements, it cannot be deemed suitable for the simulator described in this paper. The second method, direct view display, is typically implemented using LCD or plasma screens today, which also guarantee higher luminance than simple projection. Recommended luminance levels for simulators amount to 300 cd/m^2 [3]. The main disadvantage of direct view displays is typically their small distance from the pilot's eyes. When looking at a screen closer than 1 m, the pilot's eyes are focused at this distance, which can have a serious impact on his perception of distances and spatial awareness in general. This issue can be resolved by placing a collimating lens between the pilot and the screen, thus making sure that imagery of the outside world shown to the pilot is focused at optical infinity.

With regard to space limitations in the cockpit, the most suitable solution is the use of a Fresnel lens, as depicted in Figure 4. Fresnel lenses have a significantly lower weight than a conventional spherical lens of the same power made of the same material owing to the removal of lens parts not involved in refraction of light.

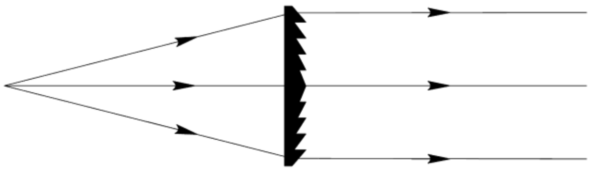

Fig. 4: Collimation.

The above principle can be used as shown in Figure 5. The top part of the outer frame consists of a Fresnel lens focusing the imagery presented to the pilot at optical infinity. The bottom part is made up of a display showing the control panel of the aircraft. This arrangement fully corresponds to reality, forcing the pilot to change eye focus based on whether they are looking at the dashboard or observing outside landscape.

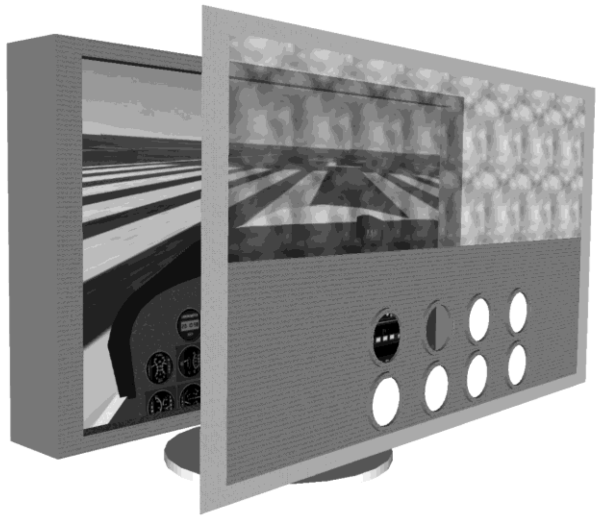

Fig. 5: Collimated direct display.

Given that the costs of producing the outer frame (including the integrated Fresnel lens) are reasonable today, the solution meets the price requirements as well.

5. Simulation of Motion Effects

Simulation of motion effects brings a simulator even closer to reality. However, this aspect of simulation tends to be neglected by some designers and manufacturers, who claim that the costs are relatively high while the benefits in pilot training remain uncertain. Several authors (for instance [3]) call into question the relevance of the concept of motion simulation in flight simulators in general. It is safe to say that for large aerospace vehicles, where acceleration levels are relatively low compared with smaller aircraft, the benefits of motion simulation can be small and implementation costs quite high. However, in case small aircraft and, in particular, land vehicles the forces acting on pilots and drivers have a significant effect on them, making motion simulation an important aspect of these simulators. In fact, training in simulators without motion simulation features can result in the trainees learning bad and potentially dangerous habits, in particular in relation to their abilities to cope with emergency situations. Motion effects are generally registered sooner than other kinds of stimuli, thus allowing undesired aircraft behaviour to be detected quickly.

Hydraulic Platform

Parallel manipulators with six degrees of freedom, or hexapods in short, rank among the most popular robotic structures used in simulation technology. This kind of a parallel manipulator has been first described by V. E. Gough [8], who constructed an octahedral platform in order to test tyre performance with regard to the effects of forces acting on them during the landing of aircraft. The first document containing a detailed description of the said kinematic structure implemented in the form of an aircraft simpit (cockpit simulator) was published in 1965 by D. Stewart [7], hence the name of the structure – Stewart platform. The Stewart platform is a closed kinematic system with an octahedral assembly of struts with different lengths and has six degrees of freedom. Its main pros, compared to other types of kinematic structures, are high structural stiffness and a high power-to-weight ratio (specific power) [9]. The structure of this device is shown in Figure 6. These parallel manipulators are capable of performing any of the six basic movement types (x, y, z, pitch, roll and yaw).

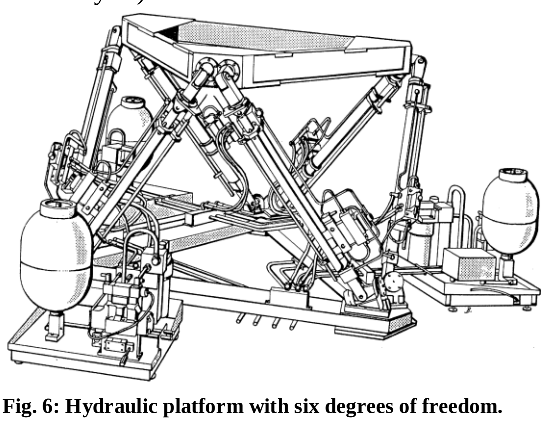

Fig. 6: Hydraulic platform with six degrees of freedom.

Simulator cockpits equipped with audiovisual and control systems are typically quite heavy. Therefore, the actuators of the kinematic structure have been implemented as hydraulic cylinders, providing high dynamics and reliability levels. Moreover, hydraulic solutions are available at more affordable prices in comparison to electrical systems of the same power.

Investigations are being made at the Department of Electric Drives and Traction of the Czech Technical University in Prague in co-operation with Pragolet, s. r. o. into the options of replacing hydraulic actuators with electric ones without detriment to the dynamic and static properties of the simulator [6]. Electric systems benefit from smaller space requirements (as it is not necessary to employ a hydraulic aggregate of sufficient power) and generate less noise at the same time. In addition, environmental aspects play a significant role too.

Figure 7 shows the dynamic properties of a hydraulic platform under full load, providing the frequency response of a hydraulic cylinder measured on a real device.

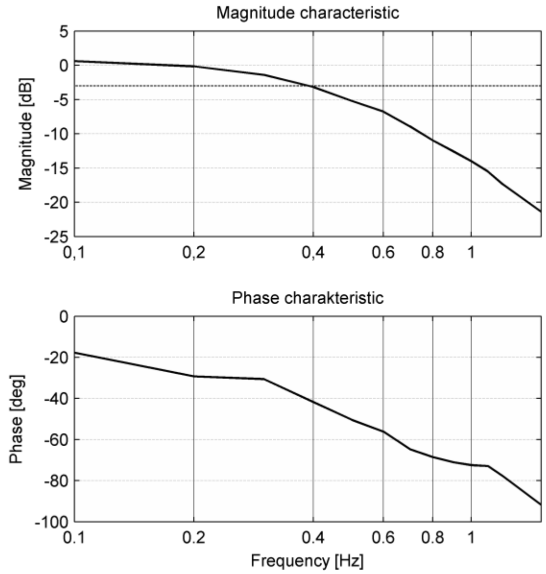

Fig. 7: Frequency response of a hydraulic cylinder.

Measured transmission band width amounted to approximately 0.4 Hz (the frequency where amplification drops to -3 dB). Experiments have proved that this dynamic level is fully sufficient for motion simulation purposes.

Inverse Kinematic Equation

The mechanical system shown in Figure 6 consists of six hydraulic cylinders attached to a pair of frames: a lower (fixed) and upper (movable) frame. Figure 8 provides a schematic depiction of the main parts of the mechanical system, indicating the parameters used in the calculation of the inverse kinematic equation.

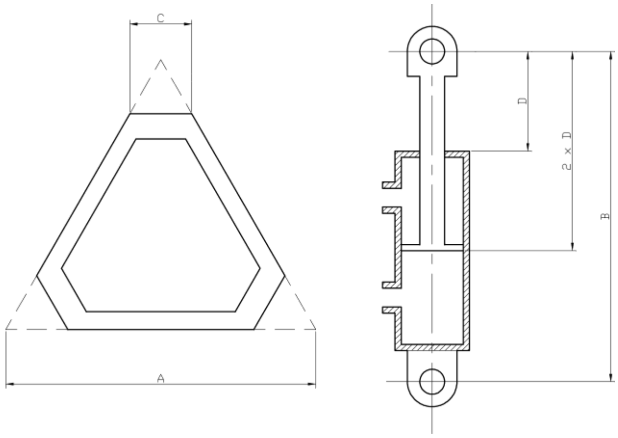

Fig. 8: Parameters of the inverse kinematic equation.

We shall define two frames of reference in this mechanical system – a fixed one (referred to as O_1) having its beginning in the centre of the lower frame, with the x- and y-axes being level with the lower frame and the z-axis parallel to the gravity vector, and a movable one (referred to as O_2) positioned in the same way at the upper frame. This essentially means that when the manipulator is idle and all cylinders are in their starting positions, both frames of reference are only shifted along the z-axis, the planes defined by the x- and y-axes of the reference frames being parallel. Now we can define and name the six possible types of movement. The upper (movable) frame of reference can rotate, with respect to the lower (fixed) system, along the x-axis, y-axis and/or z-axis. These angles shall be called φ, ϑ and ψ respectively. In addition, the upper frame of reference can move in the direction of the x-, y- and z-axes. These movements shall be called Δx, Δy and Δz. A transformation matrix **T** can be defined mapping the system O_2 to O_1:

$$\mathbf{T} = \begin{bmatrix} \mathbf{R} & \mathbf{p} \\ \mathbf{0} & \mathbf{1} \end{bmatrix}, \qquad (1)$$

where **R** is the rotation matrix and **p** the shift vector. Using homogenous coordinates the transformation matrix of a generic point can be rewritten in the following form:

$$\mathbf{x}_{\mathbf{O1}} = \mathbf{T} \cdot \mathbf{x}_{\mathbf{O2}}. \qquad (2)$$

Knowing the geometry of the base and the mutual position of both frames, we can determine the coordinates defining the position of all cylinder endings and, mapping them to the reference frame O_1, calculate the necessary displacement of the piston using the following formula:

$$v = \left| \mathbf{T} \cdot \mathbf{x}_{\mathbf{O2}}^{\mathbf{h}} - \mathbf{x}_{\mathbf{O1}}^{\mathbf{d}} \right| - v_0, \qquad (3)$$

where **T** is the transformation matrix, v_0 the length of the cylinder with the piston in its idle position, $\mathbf{x}_{\mathbf{O2}}^{\mathbf{h}}$ the position of the upper cylinder ending in the reference frame O_2 and $\mathbf{x}_{\mathbf{O1}}^{\mathbf{d}}$ the position of the bottom cylinder ending in the reference frame O_1.

The operational area of the hydraulic platform has been optimized by means of numerical iteration with respect to the requirements of the motion simulation algorithm. As shown later, the scope of rotation angle along any axis has to be at least ±30 degrees. Table 1 below shows an overview of minimum angles and ranges for all six basic movement types.

Roll	±30	degrees
Pitch	±30	degrees
Yaw	±50	degrees
Shift along x-axis	±300	mm
Shift along y-axis	±300	mm
Shift along z-axis	±150	mm

Table 1: Movement ranges and angles of the hydraulic platform.

Wash-out Algorithm

Simulation of motion effects is based on the basic principle of dynamics: When in accelerated motion, a body is affected by inertial forces acting in a direction opposite to the direction of acceleration. According to Newton's laws, this force is proportional to the mass and acceleration of the body acted upon.

As already pointed out before, the range the hydraulic platform described herein can move in any one direction is limited, the maximum distance along each axis being about 30 cm. Therefore, this linear movement alone is capable of simulating rather short accelerations only. When a longer acceleration is to be simulated, linear motion has to be supplemented with an appropriate rotation. The nature of the human vestibular system makes it impossible for us to distinguish between the feelings we experience when subject to acceleration and a situation where the simulator cockpit is turned by a specific angle, as shown in Figure 9.

The driver is under the effect of gravitational force characterized by the gravitational acceleration **g** and, in addition, affected by the inertial force **a**, thus experiencing the acceleration **k**. The relationship $|\mathbf{k}| \approx |\mathbf{g}|$ holds true for any $|\mathbf{a}| << |\mathbf{g}|$, which effectively means that the results will be the same if the cockpit is rotated by the angle φ (see Fig. 9). Mathematically, the last statement can be expressed with the formula:

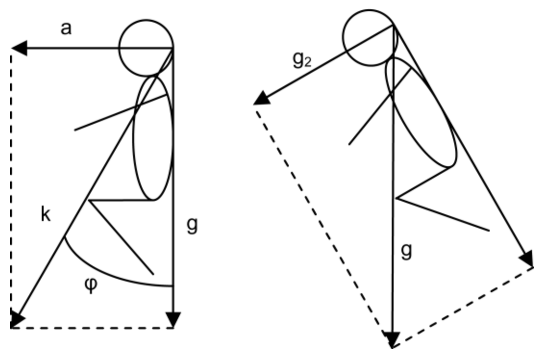

Fig. 9: Simulating linear acceleration by tilting the base.

$$\varphi = \arcsin\left(\frac{|\mathbf{a}|}{|\mathbf{g}|}\right). \quad (4)$$

The previous rule is approximately valid for accelerations of up to 5 m/s^2. In this case, the relevant angle is $\varphi = 30°$. This relationship basically determines the minimum rotation angle of the platform as specified above.

This article does not aim to provide a detailed description of the above algorithm. More information can be found in various other papers, for example [5].

6. Communication Protocol

The flight simulator described in this paper has a modular structure as shown in Figure 1. The modules (mathematical model, image generator, motion simulation algorithm, etc.) are independent units communicating with each other via a set of interfaces. In order for the model to be platform-independent, communication between the modules uses network sockets and the UDP/IP protocol, which can guarantee quick response times (the TCP/IP protocol proved to be completely unsuitable for this purpose). Potential data transmission errors are detected by cyclic redundancy checks (CRC).

Different system modules operate at different sampling rates (the mathematical model at 100 Hz, image generator at 60 Hz and hydraulic platform at 250 Hz), which can be a source of minor issues in communication synchronization. Therefore, the control system of the hydraulic platform has to be interpolated.

7. Conclusion

The flight simulator in its whole is shown in Figure 10. The cockpit with the control system and other components form a compact unit, making the simulator well-suited for transport.

Fig. 10: Finished simulator.

The main aim of this paper has been to present an overview of the status of the development of a flight simulator of light and ultra-light aircraft. The ultimate goal of the project is to design an affordable product suitable for training of sports plane pilots in flight schools. The use of simulators instead of real aircraft can significantly decrease training costs and allows the trainees to try manoeuvres which would not be safe in a real aircraft.

Further development is focused mainly on the design of flight dynamics models for other light and ultra-light aircraft, testing and improvements of the motion simulation algorithm and improvements of the visualisation module (Fresnel lens).

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