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TAMPERE UNIVERSITY OF APPLIED SCIENCES

# FLIGHT SIMULATOR DEVELOPMENT WITH SAFETY SYSTEM IMPLEMENTATION

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Bachelor's thesis
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Air Navigation Engineering

**ABSTRACT**

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In the constantly evolving aeronautical field, flight simulators are becoming increasingly common tools. Their use is being extended in both amateur and professional sectors since they provide life-like experiences effective in flight crew training from the comfort of a controlled enclosure, bringing economical benefits as well as reducing the impact on the environment.

One of the most worrisome aspects regarding to these devices is safety, since the direct contact with individuals is constant. For this reason, the aim of the project has been the performance of a safety analysis on flight simulation devices to its future implementation in the simulator of Tampere University of Applied Sciences.

In the first part of the study the basic concepts introducing the field of flight simulators have been presented, to be followed at later stage by a detailed analysis in the specific situation of the developing simulator of the university. Finally a deepening in the safety field has been performed, both in operational and general safety of the enclosure.

On the whole, the project not only provides background information on the topic and analyses closely the simulator of the university but also deepens in the safety system, allowing the implementation of the obtained results in future similar devices.

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**Key words:** flight simulator, safety

**CONTENTS**

**ABBREVIATIONS AND TERMS**

| | |
|---|---|
| BET | Blade Element Theory |
| CS-FSTD(A) | Certification Specifications for Aeroplane Flight Simulation Training Devices |
| DoF | Degree of freedom |
| EASA | European Aviation Safety Agency |
| EU | European Union |
| FAA | Federal Aviation Administration (US) |
| FFS | Full Flight Simulator |
| FS | Flight Simulator |
| FSTD | Flight Simulation Training Device (dynamic) |
| FTD | Flight Training Device (static) |
| HW | Hardware |
| IRs | Implementing Rules |
| IVAO | International Virtual Aviation Organisation |
| JAA | Joint Aviation Authorities (European equivalent of FAA) |
| JAR | Joint Aviation Requirements |
| MTOW | Maximum TakeOff Weight |
| NAA | National Aviation Authority |
| SI | International System of Units |
| SL | Sea Level |
| SW | Software |
| TAMK | Tampere University of Applied Sciences |
| TGLs | Temporary Guidance Leaflets |
| TraFi | Finnish Transport Safety Agency |
| VATSIM | Virtual Air Traffic Simulation Network |
| X-PS | X-Plane Simulator |
| ZFTT | Zero Flight Time Training |

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# INTRODUCTION

Flight simulation has evolved to become an essential component in aviation, playing a fundamental role in research, development and evaluation of aircraft and aerospace systems. Furthermore, simulation enables flight crew training with a significant reduction in economical and environmental costs, hence the method dissemination also in the amateur sector.

At Tampere University of Applied Sciences (TAMK) the interest in both aeronautical and mechanical fields has lead to the development of its own flight simulator. This project was started in autumn semester 2016 with the aim of building a realistic training tool for students and profiting from the assembly process to train as well in the mechanical and electrical fields.

However, the project does not end with the construction of the device. Once built the simulator has to be adapted to the enclosure and secured for the people going to use it. This is the foundation of the present report.

The purpose of this thesis is to do the proper research in the safety field of flight simulators in order to design a system suitable for the future installation at the university. The modifications have to be designed according to enclosure limitations and must ensure a safe operation of the system. The safety aims of this study also include the research on basic training of the users as well as the needed safety equipment in a technological laboratory. Moreover, the investigation on the safety approach of the simulator may lead to new ideas to improve safeness and the possibility to adapt them to future simulators.

The organisation of these sections is presented as follows. Firstly, the thesis provides background information about the wide field of flight simulators, giving an idea of the many uses, characteristics and classification of these devices. Secondly, detailed information about TAMK's unit is supplied, emphasising in its software and hardware features. Finally, the thesis is focused on a general safety study on flight simulators, regarding the safeness of the equipment during operation and the proper installations.

To sum up, to achieve the basic objectives mentioned at this section the thesis should be able to answer the questions hereunder:

*How flight simulators work and with which purposes?*
*Which parameters conform the simulator of Tampere University of Applied Sciences?*
*Can an efficient safety system be adapted to TAMK's upcoming simulator?*
*Can this system be applied to further simulators?*

# 1 THEORY OF FLIGHT SIMULATORS

The use of flight simulators has become widely accepted in both civil aviation and military training. Simulators allow the practice of specific levels of training as well as potentially life-threatening manoeuvres in the comfort of a training centre. Therefore, the aviation industry has led the world in the use of simulation technology to improve training and safety (Koblen 2012, [1]).

## 1.1 Introduction to Flight Simulators

A flight simulator is a device aimed to represent the conditions inside an aircraft's cockpit and the environment in which it flies in the most realistic way possible.
Using specific software and hardware, flight simulators resemble the view of the pilot with computer-generated graphs and, in some cases, even aircraft's motion.

Nowadays simulators are widely used not only as an entertainment experience but also as a training and improving tool for the aeronautical sector.

In the professional field, reliable simulations are used to train military and commercial pilots in normal situations as well as in extreme conditions that cannot be held safely in real flights. Thus flight crews improve their training to respond to hazardous situations and enable their reaction capacity in front of real flight emergencies.

Simulating usual situations helps the pilot to get familiarized with the techniques and environment of a real flight. Actually, simulators nowadays are basic tools when training pilots because they allow a good preparation in front of situations that otherwise would be catastrophic. For this reason these devices can be used as an official training method for professional pilots to obtain flight hours, but to do so the simulator has to be certified by EASA, FAA or the NAA of the respective EU member state. This qualification differs the categories of flight simulators in 4 levels from A to D depending on the similarity to the aircraft it was build for, being D the most real simulator.

Furthermore, the simulation of dangerous situations allows the improvement of devices and the specialization of the crew in front of conditions that can't be performed in real flights. This helps to enhance the effectiveness of the reaction of the pilot in case the failure actually happens. Some of those situations are: engine failure, problems with landing gear's operation, NavAid systems failure, collision with external devices, electronic failures, bad weather conditions, and much more.

Moreover, the possibility to simulate in a realistic manner all these catastrophic situations turn a good flight simulator into a basic mean to study accidents after they have happened. The repetition of the situation with the same environment and exact values used in the flight makes possible a trustable reconstruction of the actual facts. This plays an important role in aircraft design because it leads to an improvement of the parameters of the flight in order to prevent the repetition of that kind of situation.

Considering all the aspects stated above, it is clear that Flight Simulators are not only entertainment devices. A flight simulator is a useful instrument in the aeronautical sector because it enables the familiarization with tools and techniques and the study of catastrophic situations in a controlled environment, which improves the reaction of the pilot in front of disastrous conditions and allows a better development of new aircraft.

## 1.2 FS classification

A flight simulator is composed by a specific software or both software and hardware. The complexity of these elements sets the reliability of the simulation and depending on this factor these devices can be used for amateur or professional training.

According to the sensations offered by the unit, there are mainly two types of simulators: static and dynamic.

### 1.2.1 Static simulators (FTD)

Properly speaking, static simulators are not simulators itself but Flight Training Devices. They consist of a set of software and instruments that provide a realistic view out of the cockpit. Depending on the elements used and its complexity the range of static simulators embraces from computer-based games to full sized cockpits with all the necessary equipment. The first kind consists only on specific software used as a video game. Adding hardware such as immersive displays and flight control instruments turn this basic flight pretender into a much more sophisticated simulator (Picture 1.1).

**Picture 1.1** Cessna computer-based FTD with flight simulation peripheral HW (Campón 2011, [11]).

These commandments can be more or less realistic depending on the quality of the unit. According to European regulation it is determined by a number scale that runs from 1 to 7, being 1 the best qualification for aircraft simulators and 6 the worst, as 7 relates to helicopters.

A clear example of a high level simulator without movement is Pilatus (Picture 1.2), which represents the best quality FTD providing a total immersive visual and sound system.


**Picture 1.2** Pilatus PC12, level 1 FTD (Marsh 2011, [6]).

### 1.2.2 Dynamic simulators (FSTD or FFS)

Dynamic simulators, also known as Flight Simulation Training Devices or Full Flight Simulators, are much more complex devices but they result in a more realistic sensation by recreating the real movement of the cockpit. In addition to the elements of static simulators, FSTD include a motion platform that provides the cabin with movements synchronized to the ones that are being simulated.
The software, together with a machine able to run it, recreates a realistic situation that is displayed using an immersive screen system. Through the signals sent by this SW the platform, supporting the cockpit and all of its instruments, moves according to the actual recreation.

The amount of movement achieved by the simulation is introduced by the concept degrees of freedom (DoF), the number of independent parameters that define the configuration of a body. Endowing the simulator with higher values gives the cockpit a greater ability to move on different axes.

There are many types of dynamic simulators depending on the amount of degrees of freedom applied by the platform. The most common configurations are 3 DoF and 6 DoF units, however 2 DoF are also used for not-so-realistic flight simulations. The smaller the number, the cheaper the unit, so depending on the utility that will be given to the simulator a balance has to be found between these concepts.

A motion system with 6 DoF provides a highly realistic motion sensation in the three-dimensional space. It allows translation in the 3 axes (x, y and z) as well as the rotations between perpendicular planes, known in aviation as roll, pitch and yaw. The combination of all these movements results in the possibility to obtain any orientation in the 3D space from the same physical point.

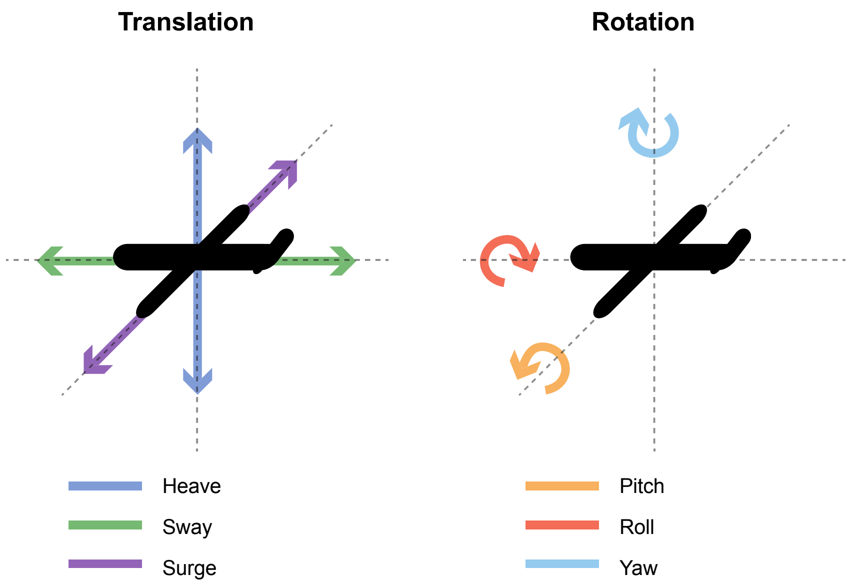


**Figure 1.1** Combination of movements in the 3D space.

A system with 2 DoF allows rotation in pitch and roll axes, while a unit with one DoF more adds the translation in the z axis, the heave motion. There are also 3 DoF devices that permit movement through the three rotation axes, not in translation, but it depends on the final use given.

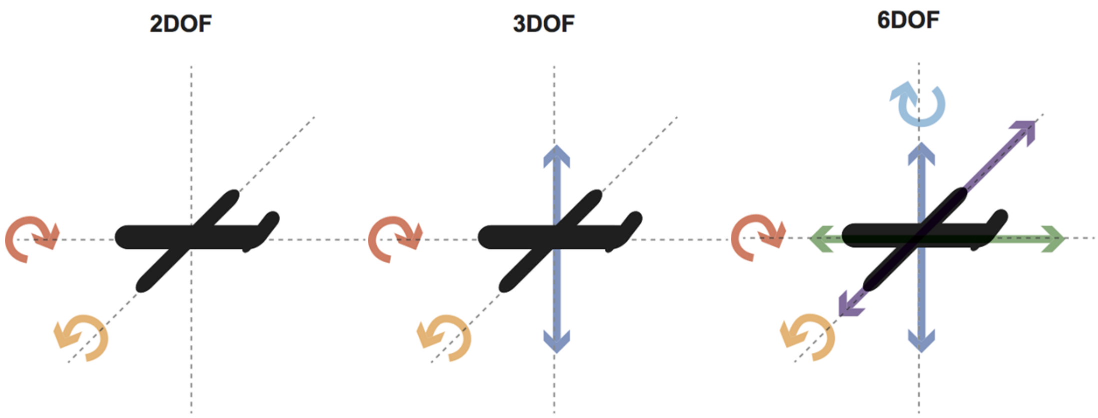


**Figure 1.2** Movements of a system depending on its degrees of freedom.

Regardless of the amount of degrees of freedom, the aim of a dynamic simulator is to be able to recreate movements such that the user feels a high level of realism in the experience. This feeling is based on the reactions of the body due to equilibrium sense in front of external sensory stimulations by combining visual, motion and audio recreations.

Equilibrium sense relies upon the cooperation of three systems: visual, vestibular and proprioception. The whole combination of senses allows a body to orientate and coordinate movements in space.

### 1.2.2.1. Visual system

It is needed to identify the direction and the speed of the aircraft using external reference points as well as to read the information given by cockpit instruments. In a simulator's environment the images generated by the computer have to be presented to the user in a peripheral vision. In order to obtain an immersive display the visual field of the pilot has to be completely filled. Otherwise, the user could suffer from motion sickness, a reaction of the body due to the confusion of the brain when visual references do not match with the motion simulated.

### 1.2.2.2. Vestibular system

Also known as the labyrinth of the inner ear, this system receives information about balance and transmits it to the structures that control eye movement and to the muscles affected by these changes.

The balance sense is obtained by the combination of two parts of the system: the semicircular canal, which indicates rotational movements and the otolith, which obtains translational movements and position due to the acquaintance of accelerations. The vestibular system can detect both static and dynamic equilibrium.

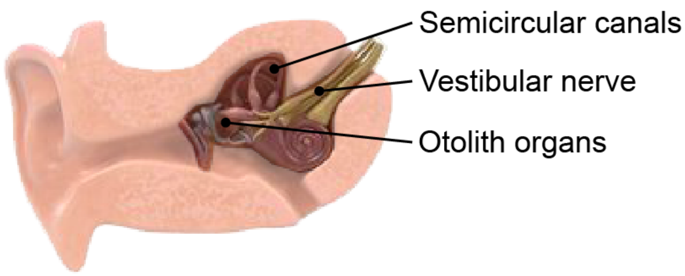


**Figure 1.3** Vestibular system location and its elements (Fajula 2006, modified, [10]).

#### 1.2.2.3. Proprioception

Proprioception is a system formed by nerves and receptors in charge of the perception of the inner state of the body. It enables automatic responses and reactions needed to survive, such as self-sustenance or coordination of basic movements. The information gathered is sent to the central nervous system where it is properly analysed and combined with the data received from the other systems.

Depending on the quality of the study of these sensory stimulations, the resulting simulator will have a higher or a lower level of realism. As said previously in this chapter, these criteria will establish the classification of simulators according to JAR regulation in a range between A to D. The basic level (A) represents the lowest requirements for system functionality, whereas the highest level (D) contains a motion system that works on six DoF and provides vibration sensations and motion effects. In brief, the best simulator is not the one with more degrees of freedom but the one with greater realism in all the parameters.

## 1.3 An optimal simulator

An ideal flight simulator is the one which can generate such realistic sensations that the user can't differ between the simulated experience and a real flight. In this case we can say the simulator is totally immersive, meaning that it provides an immersion of 100% for the user. The greater the similarities between the simulator and the corresponding aircraft better will be the adjustments to real flight conditions.

A totally immersive simulator cannot be a static device. Without motion the simulation can be of high quality but it's not fully realistic, so an ideal flight simulator should be a dynamic unit.

The better qualification among the 4 available categories for a FSTD nowadays is level D. It is certified when the platform has 6 degrees of motion and a minimum horizontal visual range of 150º with a distant focus display, to provide a great image at considerable distance. A level D FFS requires also a realistic sound system to provide the user with the right orientation skills.

**Figure 1.4** Civil full flight simulator (Allerton 2009, [2]).

Level D simulators can simulate such realistic situations that FAA allows them to provide Zero Flight Time Training. ZFTT enables experienced pilots to add to its licence an aircraft type of similar characteristics to the one already operated only by using a FFS, without actually flying the real aircraft. This reflects one of the obvious benefits of training on an effective flight simulator; the time spent training in a closed environment can replace time spent in a real aircraft reducing the danger and the cost of the learning process.

According to the gathered information, the best simulator for the moment is a dynamic unit certified with level D; 6 degrees of freedom, totally immersive and allowing ZFTT.

Nowadays there are many simulators of this kind qualified by FAA and EASA. The List of Qualified FSTD under EASA oversight [5] enumerates all the FSTD and FTD qualified by EASA on date 15th January 2017. The amount of level A or B FSTD listed is negligible in front of the hundreds of level C or D simulators catalogued. The reason is that a level 5 or greater FTD (static) generally provides a similar experience to that of category A or B flight simulators but much cheaper in comparison.

However many studies are constantly working to improve simulators and obtain experiences with greater levels of realism.

Companies as Lufthansa or Finnair use these devices to train its pilots at present. Therefore, although building this ideal simulator would cost a lot of investment, it would also entail many improvements in training and safety in the aeronautical field.

# 2 TAMK's SIMULATOR

Once obtained a general overview about flight simulators and its operation we have to establish the properties of our device. TAMK's flight simulator is expected to provide total freedom of movement to a Cessna 172 cockpit with the main purpose of students' education. To this end, it will use X-Plane operating software to do the necessary calculations and generate the graphics and a Stewart platform carried out fully electro-mechanically to give movement to the cockpit.

## 2.1 Hardware

In this section general hardware details have been depicted to obtain a better understanding on the final device.

Cessna 172 Skyhawk is a fixed high-wing aircraft with a single motor. Nowadays it is the most used aircraft for real training operations. On this account, a simulator of this plane is a practical training element for beginners as well as a good entertainment for amateurs, without requiring much knowledge in flying operations of more complex equipment.

### 2.1.1 General specifications of the model

Many performance specifications of this aircraft are taken into account in the simulated software but not in the cockpit assembly. Data as power, speeds or takeoff and landing performances are important operational parameters needed to build a realistic and consistent programme, even if they are not reflected in the physical equipment.

#### 2.1.1.1. Descriptive data

The size of a Cessna 172 is shown in Figure 2.1 extracted from its information manual [3]. The aircraft has a wingspan of 11 m, a length of 8.29 m and a height of 2.47 m.

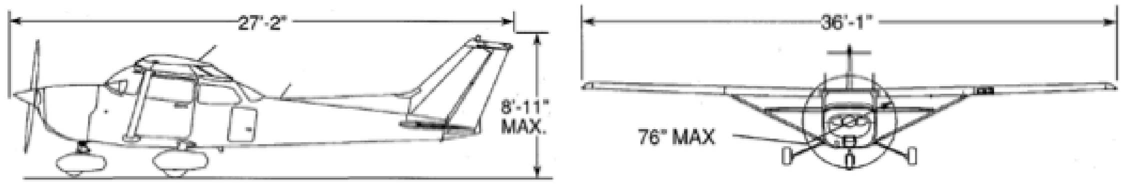


**Figure 2.1** Cessna 172S Skyhawk dimensions (Cessna Aircraft Company 2004, [3]).

Wing area of the plane is 16.16 $m^2$ and its loading 71.8 $Kg/m^2$, which sets a maximum loading of 1160 Kg. This value corresponds to the ramp weight, the biggest amount that can be supported by the plane. Taking into account the empty weight of the aircraft, the result is a maximum useful load of 405,97 Kg.

This Cessna has a single engine and a propeller with two blades, which form a 76 inches diameter and have a fixed pitch.

#### 2.1.1.2. Capacity

The plane has two fuel tanks with a total capacity of 28.0 U.S. gallons (127.29 L) each one. In total the fuel capacity rises to 56.0 U.S. gallons, though the profitable amount is 53.0 U.S. gallons. The remaining 3 are considered unusable fuel, the one that may not be available for the operation of the engine in flight because cannot be drained from the tanks. Regarding to the oil amount, the total capacity is 8.0 U.S. quarts, equivalent to 7.57 litres.

Although the simulator will not need fuel tanks nor oil, this data affects the performance of the aircraft and will be reflected in software calculations.

#### 2.1.1.3. Flight performance

The performance of an aircraft depends on its flight conditions. Cessna 172 has an operative ceiling of 14000 ft and a maximum speed at sea level of 126 kt. However, its normal operation is performed at 8500 ft with 75% of power[1], allowing a maximum cruise speed of 124 kt.

The rate of climb at sea level (SL) of this plane is 730 fpm. This parameter is reflected not only in software's calculations but also in the cockpit, since it sets the maximum angle of attack possible to achieve by the simulator before stall.

Takeoff and landing performances rely on the weight of the airplane. When taking off the craft needs a ground roll of 960 ft but when landing most of the fuel has been burnt and it only needs 575 ft to stop moving.

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[1] Recommended parameters with fuel allowance for engine start, taxi, takeoff, climb and 45 minutes reserve.

Table 2.1 sums up the main parameters of the aircraft, obtained from its information manual [3]. The software will use these data to adapt the equations that govern the movement of the aircraft and its reaction when varying control systems.

**Table 2.1** Cessna 172S Skyhawk main features (own elaboration according to [3]).

| Concept | Parameters | British Imperial[2] | SI |
|---|---|---|---|
| Size | Wingspan | 36 ft 1 in | 11 m |
| | Length | 27 ft 2 in | 8.29 m |
| | Height | 8 ft 11 in | 2.47 m |
| | Wing area | 174 $ft^2$ | 16.16 $m^2$ |
| Other | Wing loading | 14.7 $lb/ft^2$ | 71.8 $Kg/m^2$ |
| Weight | Ramp weight | 2558 lb | 1160.29 Kg |
| | Standard empty weight | 1663 lb | 754.32 Kg |
| | Max useful load | 895 lb | 405.97 Kg |
| | MTOW | 2550 lb | 1156.66 Kg |
| Performance | Max speed SL | 126 kt | 64.82 m/s |
| | Max cruise speed | 124 kt | 63.79 m/s |
| | Rate of climb SL | 730 fpm | 3.71 m/s |
| | Service ceiling | 14000 ft | 4267.2 m |
| | Takeoff ground roll | 960 ft | 292.61 m |
| | Landing ground roll | 575 ft | 175.26 m |
| Capacity | Total fuel | 56.0 U.S. gallons | 254.57 L |
| | Usable fuel | 53.0 U.S. gallons | 240.94 L |
| | Total oil | 8.0 U.S. quarts | 7.57 L |

### 2.1.2 Specifications of the cockpit and adaptation to our sim

The cockpit used in TAMK's simulator was provided by Erkki Järvinen, Air Spark Oy Chief Executive Officer (CEO), and has been adapted in order to fit all the requirements of the programme. During approximately 50 hours of complete dedication of some project members[3] many changes have been done, starting by the limitation of the

[2] System of units mainly used in Canada, United Kingdom and United States.
[3] Appendix A.

chassis and the reinforcement and reparation of the most vulnerable parts. Afterwards the inner part of the cockpit has been conditioned by the adjustment of instruments and auxiliary elements. Finally, the last point assessed has been external painting and outer design.

Taking out the unnecessary parts of the aircraft's chassis has modified the size of the resulting cockpit. The wings and the wheels have been removed, since they are not useful in a simulator. The body has also been reformed, the nose of the plane cut off and the cabin divided by half, reducing the passenger capacity. Cessna 172 accommodates 4 people including the pilot while the new cabin accommodates two people; the pilot and a second passenger aimed to teach or just observe but without access to the commands.

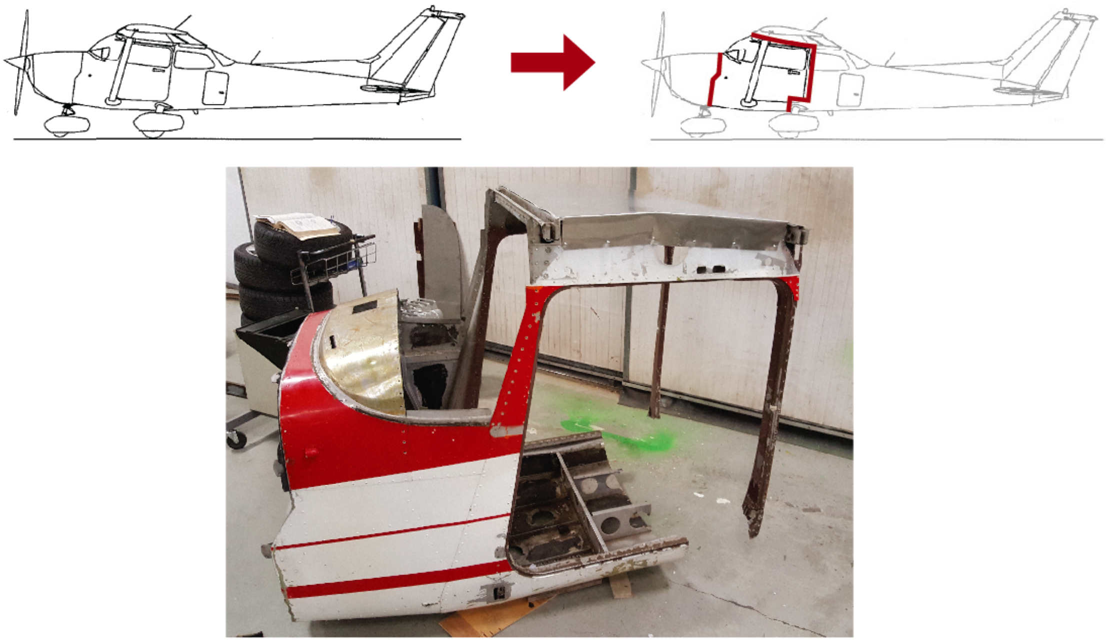


**Figure 2.2** Chassis modifications to fit the simulator. (Photo: Jarno Puska 2016).

One of the aims of these modifications is to minimize the weight of the cockpit in order to maximize the payload that the simulator can bear.

The dynamic platform sets the maximum weight it can support to keep on working properly. This weight comprises the cockpit itself and the extra load of the simulator, all the needed instruments and components as well as the pilot. Therefore, minimizing the weight of the chassis allows a greater amount of useful load.

The modifications of weight are stated in Table 2.2.

**Table 2.2** Aircraft and simulator's cockpit properties comparison (own elaboration).

| Properties | Cessna 172 Skyhawk | TAMK simulator's cockpit |
|---|---|---|
| Capacity | 4 people | Unknown for the moment |
| Empty weight | 754,32 Kg | 300 Kg – 500 Kg |
| Max payload | 405,96 Kg | 250 Kg |
| Width[4] | 11 m | 1 m – 1.5 m |
| Height | 2,47 m | 1.6 m – 3 m |
| Length | 8,29 m | 1 m – 1.5 m |

The maximum payload is one of the most important factors both in an aircraft and in a simulator, but it's important to notice that the loadings stated in the previous table cannot be compared, because they are unrelated. The payload that the real aircraft supports is determined by the wing area and its loading, while the payload that Cessna's cockpit bears is established by the resistance of the moving platform. Anyway, as said before the aim in both cases is to maximize the useful load and to do so the empty weight has to be minimized.

Furthermore, to prevent from distractions and avoid motion sickness the user inside the cockpit has to be isolated from the environment on the outside. Otherwise, the contradictory signals (motion of the simulator against static floor and walls outdoors) may confuse pilot's senses and not only reduce the reliability of the simulation but also cause motion sickness. The solution is the complete isolation of the cockpit. Everything inside the cabin but the instruments has to be black. Another colour could distract the pilot or make perceptible the presence of screens. Moreover, the cabin has to be completely closed except for the side doors, which have to be covered with black curtains.

[4] The width of the cabin is the same, but in the case of the original aircraft this value is considered as the distance from wing tip to wing tip.

## 2.2 Software

The software of a flight simulator is in charge of providing graphics, sound and instrument outputs for the cockpit.

To obtain a reliable flight experience the software needs to have access to a good processor not only for the graphical approach but also for the physics to replicate aerodynamic theory. To achieve this level of simulations the graphics have to show high-quality images and physics have to match the movements too. Replicating aerodynamic theory the physical standpoint improves, becoming more lifelike. The changes applied using the available instruments (whether they are physical outputs or displays on screen) are reflected in a realistic variation on the programme; changes are done at reasonable time and speed (not immediately), with thrust variations consistent with pilot manoeuvres and angle fluctuations in line with joystick movements and external factors.

According to this, the flight experience becomes much more realistic, being a valid tool for crew training.

However, the software of the flight simulator does not consist only of the user interface of the programme. To communicate with other parts of the simulator more elements are needed: a plugin to obtain data and determine motor angles and a microcontroller to monitor the movement of the engines via pulses.

### 2.2.1 X-Plane 10

X-Plane is a commercial, military and other[5] aircraft flight simulator as well as a learning and designing tool developed by Austin Meyer's SW company Laminar Research.

[5] Light aircrafts such as Cessna and user-designed airplanes.

After years of progress, it has become the main competitor of Microsoft Flight Simulator. Its flight model differs from others by the implementation of blade element theory (BET). This mathematical process determines the behaviour of propellers by making calculations of the thrust that produces a specific helix, modelling the forces and moments on each part of the aircraft and evaluating them independently. By this way, X-PS returns better-found data even allowing the collecting of information from user's designs, while other FS reproduce the performance of the real world only using empirical data.

The SW applies the equations that govern how the aircraft fly. Including the reaction to applications of its own controls as well as the external environmental factors, such as air density or turbulence.

In addition, nowadays it is the best simulator in the market with FAA's authorization to be used for instrumental flight pilots training. For this reason it has been considered the best SW option to be used in TAMK's simulator.

Furthermore, both aircraft and scenery are highly customizable because of their plugin architecture and the basic global scenery that covers most of the Earth, allowing the adaptation of many realistic situations.

### 2.2.2 XSquawkBox plugin

A plugin is a component that adds a new and specific function to already operational software. Due to its plugin design X-Plane is very adaptable and allows the broadening of available settings.

The plugin developed by XSquawkBox extracts information from the FS and includes a custom control system to determine motor's angles. Then, those are written in the computer serial port, from where the microcontroller reads them.

It enables also the collection of realistic air traffic data, allowing the direct connection of X-Plane with VATSIM, Virtual Air Traffic Simulation Network, or IVAO, International Virtual Aviation Organisation, both global air traffic control networks.

### 2.2.3 Arduino

Arduino is an open-source electronics platform consisting of a board with a microcontroller that reads instructions from the Arduino Software (IDE) in its own programming language. It results in an easy-to-use combination of SW and HW, which is able to read inputs and turn them into a useful output.

Arduino has a wide range of useful applications: from detecting temperatures and turning on LEDs, to reading positions and moving engines, as in our particular case.

In TAMK's project Arduino is used to control the motors via pulses. It reads the data provided by XSquawkBox plugin from the computer serial port and through an Adafruit motor shield provides power to the servo motors in order to drive them and deliver the pulses.

The code running the operations includes much precise mathematical content to ensure a proper functioning when working opposed to forward kinematics. Instead of determining the position of the platform given the positions of each actuator, inverse kinematics varies the position of each actuator in order to obtain the desired position of the platform.

The microcontroller calculates the intended position and orientation of the upper mounting points of the platform relative to the base. Then it computes the current position of the lower mounting points of the servo arm and its relative position to the base. The distance from both points is compared to the length of the connecting links and the servo arm is moved up or down accordingly.

## 2.3 Platform

The last element constituting the flight simulator is the platform. This part of the device gives movement to the whole system, making a difference between FTDs and FSTDs. In the case of TAMK's simulator, the platform is a fully electromechanical Stewart with 6 DoF.

A Stewart platform is a mechanical device used in many fields for position control. It is widely used in flight simulation, where the platform is in charge of giving motion to the user supporting the cockpit.

Actually, the specific platform used in TAMK's simulator is not a Stewart but a Thanos. The performance in both cases results in the same movements but the mechanisms applied to obtain them are different. Stewart platform implements linear motion, simplifying the final structure and reducing the risks of failure whereas Thanos applies rotatory shifts to move the arms and levers. The second one is much cheaper and easier to build, because of this it is the one applied in our simulator. However, both platforms names are generally swapped because Thanos is far less known and the final performances are equivalent.

The freedom of movement achieved by the mounted body depends on the DoF of the platform. In the case of TAMK's simulator, the device provides 6 DoF and the system is driven fully electromechanically. Using 6 rotatory motors, it transmits the accelerations to the user and together with a suitable visual system it produces the sensation of a real flight.

The Thanos platform consists of 2 rigid frames, the base and the platform itself, connected by 6 legs of variable length, as shown in Figure 2.3. The base is the reference framework providing fixed orthogonal axes and the platform's movements are done with respect to them. As already explained in Section 1.2.2, the translational displacements of the platform set its origin of coordinates while the angular displacements define its orientation with regard to the base.

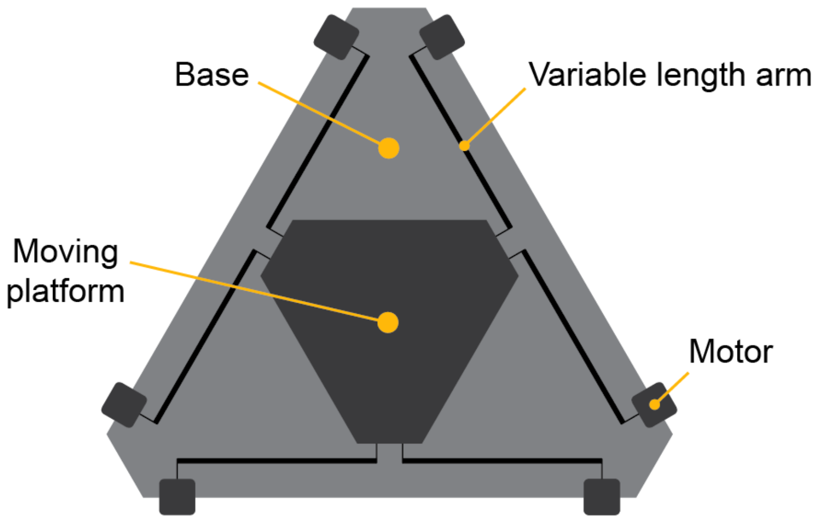



**Figure 2.3** Thanos platform top view drawing.

According to these concepts, the electromechanical system uses electrical signals to create a mechanical movement. In the case of TAMK's simulator data is processed and controlled by Arduino and then it computes the positions and determines the physical movement of each rod. The RC servos receive the information and through rotation they move the arms and vary its length in agreement. The servo motors rotate at 1500 rpm transmitting to each gearbox 18 rpm, increasing its torque to 500 Nm. In this step velocity is reduced in order to increase the available power.

Figure 2.4 shows the elements connecting the fixed base with the platform. Each engine is attached to a gearbox that gives motion to the rotatory assembly element, adjusting the direction and length of the arms to obtain the desired final position of the cockpit.

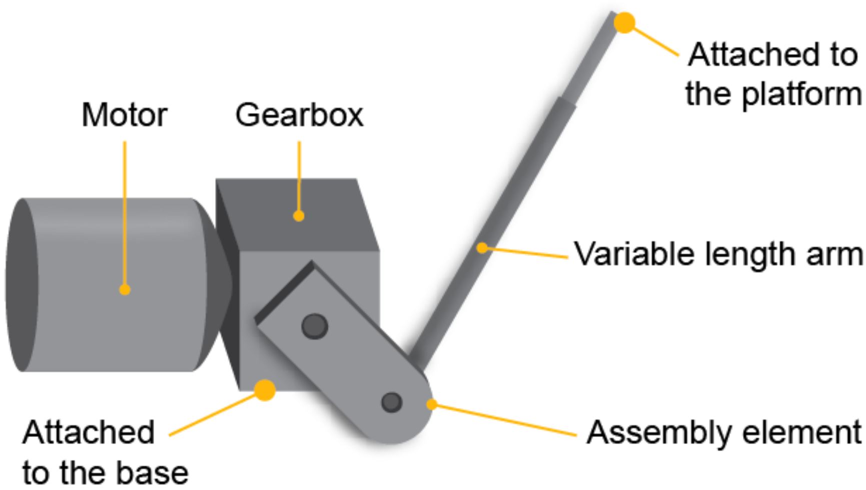



**Figure 2.4** Detailed sketch of the elements connecting the fixed base with the moving platform.

It is preferable to use short arms to move the platform. Long rods are less durable and by minimizing the length the risk of falls is reduced and the safety of the device improved. For this reason a Stewart platform is safer, the final structure is simpler with shorter arms.

However, as all the mechanical designs it has some performance limitations. Each of the arms moving the platform used in our simulator has a freedom of ±70°. This means that if all the elements are working properly the rods should not deviate more than 70º from its initial position. This is reflected in a maximum inclination of the platform of ±15° and limits in angular speed and acceleration of ±15°/s and 150°/s$^2$ respectively.

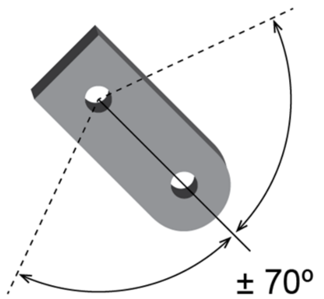



**Figure 2.5** Limitation in rotation of a frame element.

## 2.4 Location

The cockpit is currently at Air Spark Oy centre, an aviation company based in Pirkkala where the main chassis adaptations have been done. It is a proper placement, though due to other considerations the simulator is aimed to be enclosed at Tampere University of Applied Sciences' main campus.

One of the most important factors is the weight. The floor of the enclosure containing the simulator has to be able to withstand the load of the whole assembly and face sudden movements without problem. Air Spark centre gathers those conditions, while TAMK's situation is a bit more complicated. It will be placed in the 2nd floor, so the foundations of the building have to bear the entire load. To ensure it and work in safe conditions the constraints in payload capacity of the simulator have been downsized, setting a maximum payload value lower than the actual limitation.

Another factor to consider in the location is the accessibility to make technical changes in the workplace. If the simulator fails in some aspect it has to be fixed without the need of disassembling.

Finally, the last consideration is the comfort. In order to foster the use of the simulator it has to be conveniently located. Air Spark Oy is in the region of Pirkkala and needs to be reached by bus or car, about 25 minutes from Tampere, while TAMK's location is easily accessible from any point of the city.

Although it has been agreed that the simulator is going to be placed at TAMK, it is preferable to leave it in Air Spark Oy while it is under construction and the cockpit is not being used. This way any possible change required can be done in a better prepared environment than the university itself. Consequently, when working in that area the company premises have to be fulfilled.

# 3 SAFETY STUDY

The main concern in every system involving human participation is safety. A flight simulator is a complex device aimed to be operated by users so it must be robust and fail-safe. To this end a proper study must be done, reducing the probability of accidents during the operation and ensuring a safer and faster response in front of possible failures.

In the particular case of flight simulators a complete safety study should include research on the applicable directives as well as an analysis on the required equipment and procedures.

## 3.1 EU safety directives

Aviation is underpinned by safety. The main role of the aviation authorities is to ensure a safe development of all aircraft operations, including flight training.

In Europe the safety in civilian aviation is regulated by the European Aviation Safety Agency (EASA) [7]. The responsibilities of this authority include the analysis and control of safety parameters involved in aeronautical devices to ensure a proper and safe operation. EASA Certification Specifications are used to demonstrate compliance with the Basic Regulation [6]and its IRs.

In the case of flight simulators Certification Specifications for Aeroplane Flight Simulation Training Devices (CS-FSTD(A)) [4] describe the requirements a FSTD has to fulfil in order to obtain a specific level of qualification and maintain it. The evaluation consists in the implementation of technical standards and validation tests as well as functions and subjective tests.
As each aircraft product, a flight simulator has to be subject to various analysis and standards. Those are gathered in CS-FSTD(A) and widely explained at JAR-FSTD A and JAR-FSTD TGLs.

[6] Regulation (EC) No 216/2008 of the European Parliament and of the Council of 20 February 2008.

In addition to the compliance with the regulation, EASA also controls the maintenance of the qualification level as well as the proper formation for all the users in contact with the simulator.

However, TAMK's simulator parameters do not comply the minimum requirements to obtain a certificate for any qualification level. That is to say our simulator does not meet the specifications needed for commercial use in pilot training, though it can be used as an educational device.

Regarding to regulation compliance, the fulfilment of European general directives is supervised separately in every country by its local authorities. In Finland the agency monitoring the safety control in civil aviation is the Finnish Transport Safety Agency (TraFi). Nevertheless, as the simulator is not aimed to professional training TraFi is not in charge of safety supervision. As a consequence the entity responsible for EU directives compliance is the simulator's supervisor.

The FSTD operator shall ensure that the device and the whole installation comply with the local regulations for health and safety. Moreover, every user in contact with the simulator, both occupants and maintenance personnel, need to be formed in safety equipment and procedures to guarantee an efficient response in case of emergency.

The operator of the simulator shall also check at least annually the proper functioning of all the emergency features such as stop devices or specific lighting.

To sum up, the EU safety directives do not require a qualification level certificate to a flight simulator not aimed at professional training. However, the regulation affecting it establishes that the installation must comply with the general safety standards of a technological laboratory and that the people in contact with the simulator have to be trained in safety procedures. The directives also establish that any misuse of the simulator will fall on the supervisor.

## 3.2 Operational safety system

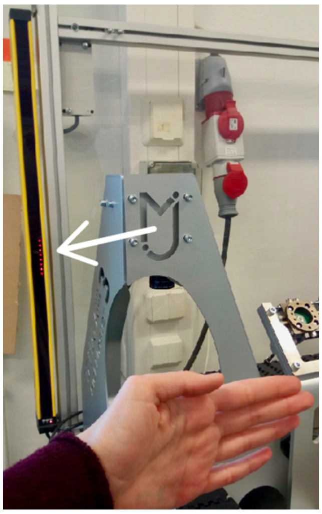
A flight simulator is a complex system and as such it is susceptible to both electric and mechanical failures. To prevent the system from hazards that may injure simulator's users the adaptation of some features and safety procedures is required.

### 3.2.1 Mechanical risks

To avoid malfunctions of the system due to mechanical failures it is necessary to implement preventive maintenance procedures to guarantee safety. This monitoring lies on the operator of the simulator and has to be performed at least annually to avoid degradation of the system.

Moreover, to avoid personal injuries within the enclosure of the simulator because of mechanical elements it is necessary to keep a safety distance to the mobile parts of the device, specifically the platform. To this end, it is necessary to install a system aimed at the stop of movement in case the established safe area is surpassed. The suitable element is a fence, which can be either electronic or physical.

An electronic fence is a movement detector. It consists of a set of sensors surrounding a closed area, which use InfraRed rays to detect any movement in the protected perimeter. These sensors are activated if the perimeter is surpassed (Picture 3.1), in which case the simulator is turned off immediately to prevent any personal damage.



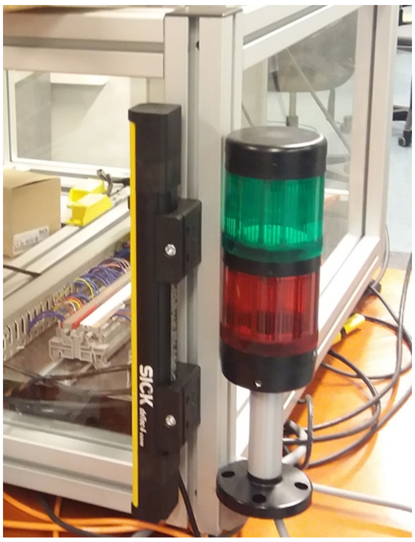
**Picture 3.1** Electronic fence of TAMK's robotics laboratory. The red dots marked with an arrow show that the hand is surpassing the safety perimeter. (Photo: Berta Martínez 2017).

Prompt stops of the system can be dangerous to the pilot using the simulator but must be feasible in order to protect observers from possible damages caused by the movement of platform's mechanism. Therefore, to keep the pilot safe without endangering other users it is essential the use of a seatbelt when flying the simulator.

The second option is a physical fence. A panel enclosing the simulator is a clear separation between the observer and the moving platform. In case the door is open the motion of the simulator is interrupted and remains paused until the fence is completely closed again. The door has to be an easy-opening mechanism to allow a fast reaction in case the pilot needs to be assisted.

The main advantage of an electronic fence in front of a physical one is the visual field and the accessibility. A panel between the observer and the simulator impairs vision of the actions performed behind it, while a group of sensors does not. However, a physical fence provides a higher degree of safety. The limitation is obvious preventing unnecessary stops due to observer's careless distance surpass, which results in safer protection for both pilot and observer.

According to this information, the protective fence that fits best a flight simulator is a hurdle made of fire retardant and preferably see-through material. Thus, the fence does not only protect against physical damages but also against possible electrical shock.




**Picture 3.2** Lighting warning system. (Photo: Berta Martínez 2017).

In addition, it has to be endowed with a safety lighting system (Picture 3.2) consisting of green and red warning lights. The red indicator is activated while possible danger is considered due to the opening of the door and the green light is punctually activated when the system recovers its usual operation. This lighting system gives to every user of the simulator a clear understanding of the situation.

### 3.2.2 Electrical risks

In the event of electrical failure the simulator needs a proper equipment to allow a safe evacuation of the cockpit. The access to the cockpit can only be performed when the platform is levelled. In case of power outage during the operation of the simulator the cockpit can be left in any position, hindering the safe evacuation of the pilot. To solve this situation it is necessary to install an external battery that provides power to the system in case the electricity grid does not. This source is not aimed to the normal operation of the simulator but strictly to safety purposes.

Moreover, a proper emergency lighting system must be installed to leave the enclosure. In case of power outage a set of indications have to ensure an easy evacuation from the cockpit to the exit door. This lighting system must remain illuminated while emergency buttons are pressed.

### 3.2.3 Software limitations

In terms of safety, another operational adaptation of the system is the implementation of software limitations. The SW has to be designed with constraints to avoid movements unattainable for the platform. For instance, if the aircraft goes into spill or makes a barrel roll the mechanism of the platform cannot perform such movements. Therefore, the programme has to adapt the code adding exceptions when flight parameters exceed the security margin established.

## 3.3 General safety equipment and procedures

The enclosure of the simulator has to comply with the general safety regulations of a technological laboratory. The required equipment must be inside the laboratory. Since the machinery being operated is big and complex the risk in case of accident is high so the necessary elements to react in this situation must be as close as possible without affecting the normal operation of the installation. A possible distribution is sketched at Appendix C.

The equipment includes extinguishing material, emergency stop buttons, phone, medicine cabinet, water point and first aid equipment.

### 3.3.1 Emergency shutdown system

The simulator has to be equipped with an effective shutdown system. It consists of two emergency stop buttons; one located outside the simulator and the second one inside the cockpit.

The switch placed outside Cessna's cockpit is the main control, giving power to the system. In front of the panel where the button is placed there must be at least a free space of 1 meter to facilitate the access. It has to be readily available for the outer users in order to ensure a fast response in case the pilot is not capable of reacting.

**Picture 3.3** Panel of emergency buttons in one of TAMK's laboratories. (Photo: Berta Martínez 2017).

On the other hand, the button inside the cockpit permits the pilot to level it and stop movement at any moment during the simulation. It should not be used as the main stop switch but in case of emergency pilot's safety cannot only rely on outside users. The switch has to be accessible without disturbing the normal operation of the simulator, so it should not be near aircraft's instruments.

In case any of the buttons is pressed the electricity is cut off throughout the laboratory but the battery (mentioned in section 3.2.2) is activated, since the simulator has to be levelled to allow the exit of the pilot.

### 3.3.2 Electric accidents or fire

In the event of an electrical failure or presence of fire, the necessary equipment consists of a carbon dioxide extinguisher, a fire alarm, a phone and the necessary units to assist injured people. Other laboratories include in its equipment a fire hose or automatic fire extinguishers, but in TAMK's simulator enclosure those instruments are not an option because water would aggravate the situation due to the presence of electric devices.

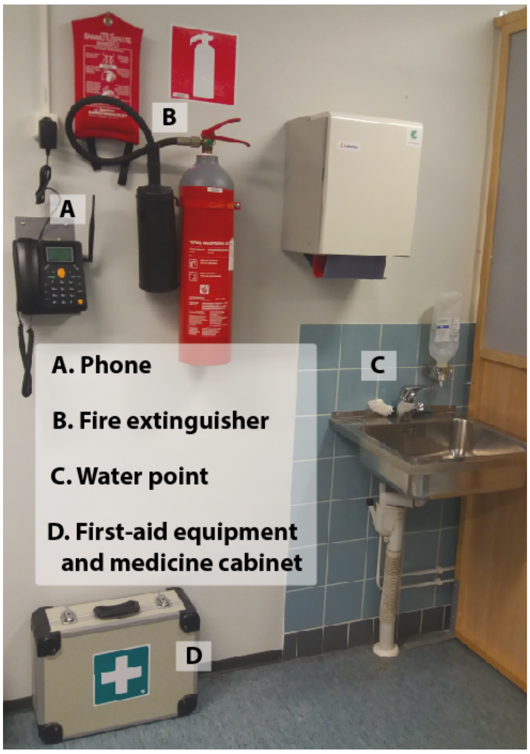



**Figure 3.1** Safety equipment inside the technological laboratory, separated from simulator's area.

The procedure that must be followed in both situations is similar, but the order in which actions are performed varies slightly.

In case there is fire in the installation first of all the user has to use an emergency stop to turn off the power. Secondly a phone call must be done to alarm 112. That is a further reason why the minimum occupation of the enclosure must be two when the simulator is operating; the subject not flying the device can access rapidly to the phone provided and raise the alarm. After that the user shall perform a rescue operation if it does not endanger himself, on the contrary he will proceed to the next step: use of the fire extinguisher.

In the event of an electric accident the situation can be critical because it generally implies injured persons. For this reason first aid equipment, a medicine cabinet and a water point must be placed near the entrance of the enclosure.

Firstly the electricity must be cut off and immediately after that the wounded must be located in a safe place for treatment, preferably outside the simulator's enclosure. Only after this procedure emergency service must be alarmed.

## 3.4 Rules and user training in safety procedures

"The best safety device in any aircraft is a well-trained crew." (Ueltschi 1951, [8]).

To guarantee an effective response in case of emergency both occupants and maintenance personnel of the simulator need to be formed in safety equipment and procedures.

The most important rule in simulator's safety conditions is the need to use it in presence of another subject. This minimum is established for the purpose of having the situation under control all the time, this way in case of accident or injured people warning can be done much faster. Moreover, there must be determined a limit of maximum occupancy in order not to throng the enclosure.

To access the simulator users must have the proper formation in reanimation procedures in case an electric accident happens. Anyone entering the laboratory must also be familiarized with simulator's operation and safety equipment and procedures. Thereby, there is no need to have a supervisor present during the operation of the simulator. To ensure the limited access the simulator is separated from the common area requiring a validation or key to enter the operational zone. This separation already exists in the laboratory (Picture 3.4).

**Picture 3.4** Separation inside the laboratory between the common area and the simulator.
(Photo: Berta Martínez 2017).

People without proper training must not enter the enclosure without prior consent. Therefore, opening the door to unauthorised users is totally forbidden.

General safety regulations in TAMK's laboratories [9] establish that considering a great number of people able to access a laboratory every working group must appoint a responsible of the activity. This subject must ensure the operation in accordance with safety instructions and control its continuous compliance.

Before starting the operation of the simulator the designated responsible must check the correct functioning of the device. Moreover, any damage to the equipment must be immediately notified to be fixed at the earliest.

According to maintenance procedures, the staff must ensure circuit is not powered while performing the operations. The electric grid must be switched off in advance.

Furthermore, to prevent users from endangering themselves the clothing has to be appropriate. Garments as sandals or long gowns can compromise safety when using simulator’s pedals or other instruments. Moreover, coats, bags and other unnecessary accessories or equipment must be left outside the facility.

To sum up, in order to be trained in safety procedures and be able to access the simulator’s premises a user must be formed in safety and reanimation procedures as well as be aware of the standing rules of the laboratory.

# 4 CONCLUSIONS AND DISCUSSION

A flight simulator without safety adaptations turns to be a useless device since it cannot be operated nor used as a training method. The development of this thesis has lead to the design of a complete safety system for the flight simulator aimed to be enclosed at TAMK.

The resulting plan has drawn from a theoretical study adapted to the current situation at university. Security elements have been roughly designed, without an in depth analysis of structure or materials but a detailed study in placement and safety needs.

The development of this study proves that the design of a helpful safety system involves many parts linked together that have to be studied in detail to ensure a proper operation. The basic parameters have been developed and properly organised although many adjustments can still be performed to increase the effectiveness of the installation in the near future.

In order to improve safety, in a future could be considered the enlargement of the current enclosure by removing the wall panel of the laboratory. A bigger installation would leave room to operate more comfortably and reduce the reaction time in case of emergency since elements in the laboratory would be more widely separated and the free-distance in front of the main switch could be grater than 1m.

Further potential research could be a study to turn this simulator into a qualified device. To obtain a qualification level it would need to pass stringent validation tests and verifications to comply with EU directives, meaning a complicated and expensive procedure, however it would allow a leap into the professional training field.

Finally, with this project it is proven that building a six degrees of freedom simulator is feasible and a security system can be adapted to it independently from the chosen enclosure.

Moreover, answering to the initial question yes; this safety system can be applied to other simulators provided that they don't need a qualification level. This study ensures safety of every individual using the simulator but is not subject to EU directives approval. In case a simulator needs to obtain a qualification level this system can be applied, but only as a guide to obtain a perfected system.

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**APPENDICES** 1 (2)

Appendix A. Project members

**Project manager:** Jarno Puska
**Project members:** Walter Clee, Oula Kinnunen, Harri Paju, Ville Pekkarinen, Niklas Peltonen, Jarno Puska.
**Mentors:** Mika Ijas, Ville Jouppila, Antti Perttula, Mikko Ukonaho.

TAMK’s simulator building is a complex project concerning many people working in different fields. Currently there are 10 people involved in the programme; 6 working actively and 4 as mentoring assistants.

An overview of the main work assigned to each member is depicted as follows.

Jarno Puska is in charge of the project plan. Together with Harri Paju and Niklas Peltonen they deal with the electric part of the design as well as the integration and testing of the system using simulations. This group is also involved in safety and system in use evaluations.

On the other hand, Walter Clee, Oula Kinnunen and Ville Pekkarinen handle the changes applied to the Cessna body by performing the necessary calculations. In addition, they are in charge of the relevant checks and tests to ensure the proper implementation of the physical modifications.

The faculty members mentoring the project in the field of mechanical engineering are Mika Ijas, Ville Jouppila, Antti Perttula and Mikko Ukonaho, contributing expertise in intelligent machines and strength of materials.

Itemizing the project in individual phases the authorship of each process is the following.

1. Simulation of electromechanical and hydraulic actuators using Matlab software.

    Harri Paju

    Niklas Peltonen

2. Modifications of Cessna's cockpit to adapt the simulator.

    Ville Pekkarinen

    Oula Kinnunen

    Walter Clee

3. Electromechanical structure design. Study and determination of actuators and support frame.

    Harri Paju

    Niklas Peltonen

    Jarno Puska

4. Electrical engineering design and implementation.

    Harri Paju

    Niklas Peltonen

    Jarno Puska

5. Study and determination of components and materials.

    Harri Paju

    Niklas Peltonen

    Jarno Puska

6. System integration. Testing and documentation of guidance for the device.

    Harri Paju

    Niklas Peltonen

    Jarno Puska

This appendix gathers some additional images and sketches acquired during the building of the simulator in order to obtain an overall perspective and a better understanding on the assembly process.

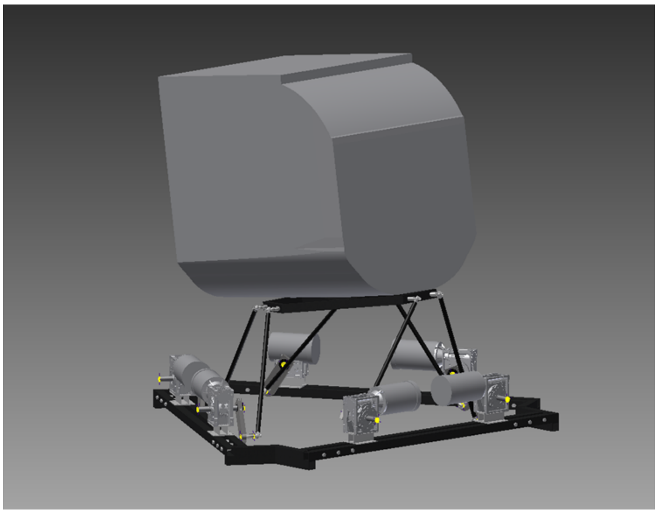


**Figure B.1** Prototype of the simulator designed by project members with Autodesk Inventor Professional 2014 (Jarno Puska 2017).

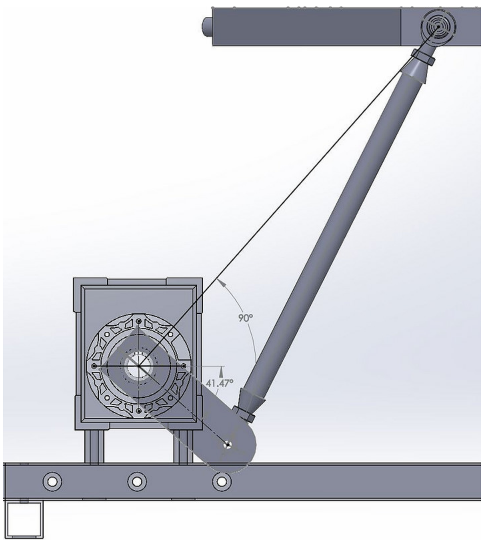
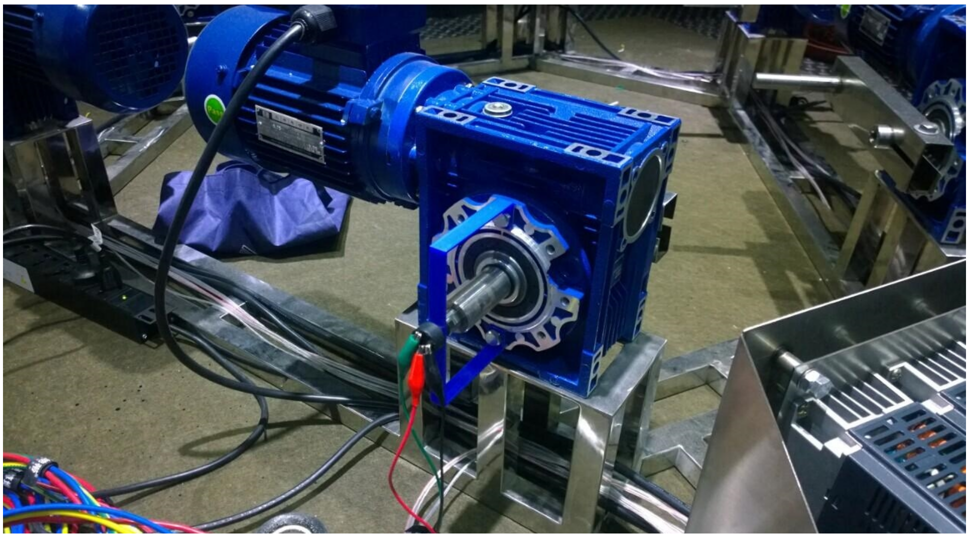
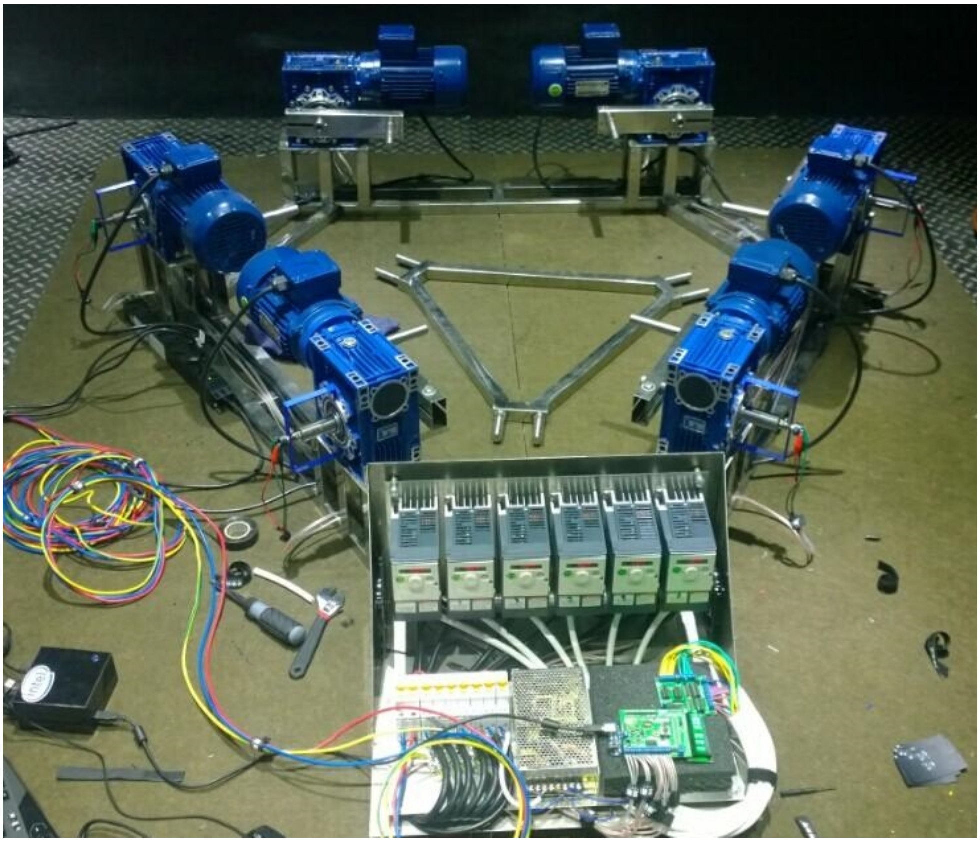



**Figure B.2** Structure of the elements joining one of the gearboxes to the moving platform. The length of the arm is such that allows a safe movement of the cockpit. This sketch has been also plotted by project members with Autodesk Inventor Professional 2014.



**Picture B.1** Detailed image of the engine and the gearbox. This picture does not correspond to TAMK's simulator but the one used has the same appearance. (Photo: Harri Paju 2016).

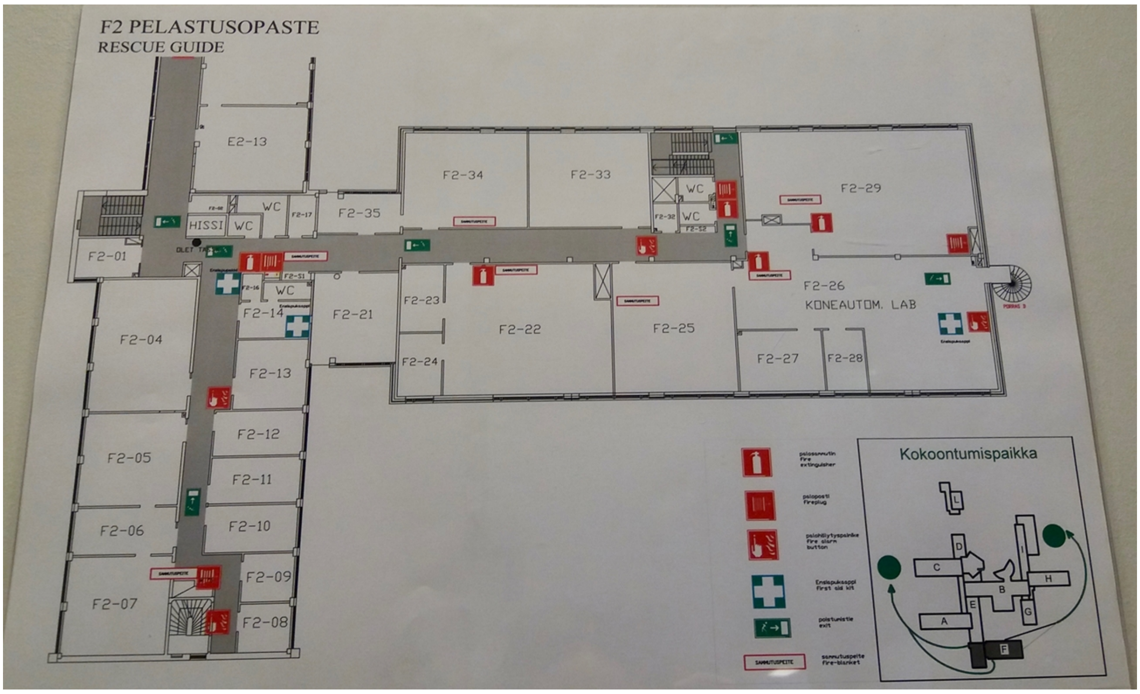


**Picture B.2** Fixed base structure with components at the final position. The central triangle is the frame of the moving platform. (Photo: Harri Paju 2016).

**Picture B.3** Project members working on the adjustment of the cockpit. The inner modifications include the installation of cockpit instruments in the front panel as well as the structure enhancement. In the picture project members are working on the adaptation of the cockpit floor. (Photo: Jarno Puska 2016).

**Picture B.4** Reparation and adjustment of the ceiling after wings removal. In the picture the tail of the aircraft has not been completely removed. (Photo: Jarno Puska 2016).

**Picture B.5** Workspace in AirSpark Oy center. (Photo: Jarno Puska 2016).




**Picture B.6** Rescue guide. Emergency exit of TAMK's building F 2nd floor. The laboratory where the simulator is placed is F2-22. (Photo: Berta Martínez 2017).

Appendix C. Laboratory plan and safety elements distribution