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ÚSTAV POČÍTAČOVÉ GRAFIKY A MULTIMÉDIÍ

FLIGHT DATA VIZUALIZATION

VIZUALIZACE LETOVÝCH DAT

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

AUTHOR

AUTOR PRÁCE

MICHAL TABÁŠEK

SUPERVISOR

VEDOUČÍ PRÁCE

doc. Ing. PETER CHUDÝ, Ph.D. MBA

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Bachelor's Thesis Specification

For: **Tabášek Michal**

Branch of study: Information Technology

Title: **Graphical Interface for Flight Displays**

Category: Computer Graphics

Instructions for project work:

1. Research the aircraft equations of motion.
2. Get familiar with past, state-of-the-art and future flight data visualization trends.
3. Design graphical interface for flight displays.
4. Implement your display design into the aircraft simulator located at FIT.
5. Evaluate achieved results and discuss potential further improvements.

Basic references:

- According to supervisor's recommendations.

Detailed formal specifications can be found at <http://www.fit.vutbr.cz/info/szz/>

The Bachelor's Thesis must define its purpose, describe a current state of the art, introduce the theoretical and technical background relevant to the problems solved, and specify what parts have been used from earlier projects or have been taken over from other sources.

Each student will hand-in printed as well as electronic versions of the technical report, an electronic version of the complete program documentation, program source files, and a functional hardware prototype sample if desired. The information in electronic form will be stored on a standard non-rewritable medium (CD-R, DVD-R, etc.) in formats common at the FIT. In order to allow regular handling, the medium will be securely attached to the printed report.

Supervisor: **Chudý Peter, doc. Ing., Ph.D. MBA**, DCGM FIT BUT

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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
Fakulta informačních technologií
Ústav počítačové grafiky a multimédií
602 00 Brno, L.S. Jeřábekova 2



Jan Černocký

Associate Professor and Head of Department

Abstract

This bachelor thesis deals with the flight data visualization. It contains a description of the airplane mathematics and physics model, instruments used for flight data visualization and process of creating a primary flight display for flight simulator. The display is created using C++ language and OpenGL graphics library.

Abstrakt

Tato bakalářská práce se zabývá vizualizací letových dat. Obsahuje popis matematicko fyzikálního modelu letadla, přístrojů používaných při zobrazování letových veličin a proces vývoje primárního letového displeje pro letecký simulátor. Displej je implementován s využitím jazyka C++ a grafické knihovny OpenGL.

Keywords

primary flight display, avionics, aircraft, flight data visualization, flight simulator, mathematical model of an airplane, C++, OpenGL

Klíčová slova

primární letový displej, avionika, letectví, vizualizace letových dat, letecký simulátor, matematický model letadla, C++, OpenGL

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Flight Data Vizualization

Declaration

Hereby I declare that this bachelor's thesis was prepared as an original author's work under the supervision of doc. Ing. Petr Chudý, Ph.D., MBA All the relevant information sources, which were used during preparation of this thesis, are properly cited and included in the list of references.

.....
Michal Tabášek
May 18, 2017

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Acronyms and Abbreviations

ACFD	Advanced Civil Flight Deck
ADI	Attitude Direction Indicator
ALT	Altitude
A/P	Autopilot
ATC	Air Traffic Control
BFF	Body Fixed Frame
CRT	Cathode Ray Tube
CG	Center of Gravity
ECEF	Earth-Centered Earth-Fixed System
FD	Flight Director
FMS	Flight Management System
FSWG	TriService Flight Symbology Working Group
GPS	Global Positioning System
HUD	Head-Up Display
HSI	Horizontal Situation Indicator
IIS	Integrated Information Systems
ILS	Instrument Landing System
IRP	International Reference Pole
IRM	International Reference Meridian
LCD	Liquid Crystal Display
ND	Navigation Display
NED	Local North-East-Down System
OCIDIS	One Display for a Cockpit Interactive Solutions
OIS	On-board Information System
PFD	Primary Flight Display
QNH	Atmospheric Pressure
RAF	Royal Air Force
SESAR	Single European Sky ATM Research
STD	Standard
TAS	True Air Speed
TCV	Terminal Configured Vehicle
USAF	United States Air Force
VSI	Vertical Speed Indicator

VNAV
WGS

Vertical Navigation
World Geodetic System

List of Symbols

Greek Symbols

Symbol	Unit	Description
α	[°]	Angle of Attack
β	[°]	Angle of Sideslip
λ	[°]	Longitude
μ	[°]	Latitude
ϕ	[°]	Roll angle
ψ	[°]	Yaw angle
θ	[°]	Pitch angle

Roman Symbols

Symbol	Unit	Description
f_x, f_y, f_z	[m s ⁻¹]	Specific forces
h	[m]	Altitude
I_X	[kg m ⁻²]	Moment of inertia about body x-axis
I_{XZ}	[kg m ⁻²]	Product of inertia with respect to X and Z body axes
I_Y	[kg m ⁻²]	Moment of inertia about body y-axis
I_Z	[kg m ⁻²]	Moment of inertia about body z-axis
L, M, N	[kg m ⁻²]	Another moments
M_0	[m]	Meridian radius of curvature
N_0	[m]	Prime vertical radius of curvature
\dot{p}	[rad s ⁻²]	Airplane roll acceleration about body x-axis
p	[rad s ⁻¹]	Airplane roll rate about body x-axis
\dot{q}	[rad s ⁻²]	Airplane pitch acceleration about body y-axis
q	[rad s ⁻¹]	Airplane pitch rate about body y-axis
\dot{r}	[rad s ⁻²]	Airplane yaw acceleration about body z-axis
r	[rad s ⁻¹]	Airplane yaw rate about body z-axis
u, v, w	[m s ⁻¹]	Components of airplane velocity along body x-axis, y-axis, z-axis
V	[m s ⁻¹]	Airplane resultant velocity

1. Introduction

Only 114 years divide generation from the first flight performed by the Wright brothers in 1903, till the state of the art aircraft that fly above the heads of million of people every day. From the desire to keep the aircraft in the air for only few minutes, people are now in that time where airlines compete between each other in the length of the most longest flight. The Emirates airline is currently holding the world record far longest non-stop flight. They have managed to conduct flight in a duration of a 16 hours and 23 minutes while flying 14535 km distance [38].

Looking at the development from a different angle, the events in last century motivated an increased demand on transportation safety, aviation technology and pilot training.

The most significant channel is stimulating pilots, situational awareness uses the process visual of information, more specifically the information represented through the visualization of the flight data. Due to its importance, the flight data visual representation is the main scope of this thesis.

The thesis itself is divided into 10 chapters. The first chapter introduces the basics of flight mechanics through the aircraft equations of motion. The second chapter provides an insight into the past, state-of-the-art and future of flight data visualization trends. The following, third chapter, deals with the design of graphical interface for flight displays. Subsequent fourth chapter describes the implementation procedure of the author's display design and its implementation into an aircraft simulation located at the Faculty of Information Technology of the Brno University of Technology. The thesis is concluded by the chapter describing the evaluation of the proposed design and an outlook for potential future improvements.

2. Airplane equations of motions

This chapter will describe the aircraft equations of motion used to obtain the flight relevant quantities to be displayed to the pilot in the cockpit. Utilized coordinate systems are described in the first section. The knowledge of the specific coordinate system belongs to the basic knowledge of the aircraft modeling and simulation. Another section will deal with the aircraft equations of motion.

2.1 Coordinate Systems for Aircraft

For the purposes of this chapter, the coordinate systems can be divided into two groups. The first group is composed of coordinate systems related to the navigation or ground coordinate system and includes the Earth-Centered Earth-Fixed system, the North-East-Down system and the World Geodetic System. The second one is related to the applications in which the first group is integrate with other sensors (such as speed and heading sensors) and includes the Body Fixed Frame and the Aerodynamic coordinate system [32].

Earth-Centered Earth-Fixed system

The Earth-Centered Earth-Fixed coordinate system is known as abbreviation ECEF. The ECEF coordinate system is defined as a right-handed Cartesian system, whose origin coincides with the Earth's center of mass. The x-axis points to the mean Greenwich meridian, the y-axis is directed to complete a right-handed system and the z-axis points to a Conventional International Origin (CIO) of the Earth's rotation.

The location of the center of the Earth is defined by the International Terrestrial Reference System (ITRS) [31]. The ITRS is geocentric non-rotating system with the center of mass defined for the whole Earth, including oceans and atmosphere. The ITRS definition fulfills several another conditions, which includes unit of length, and time conditions [32].

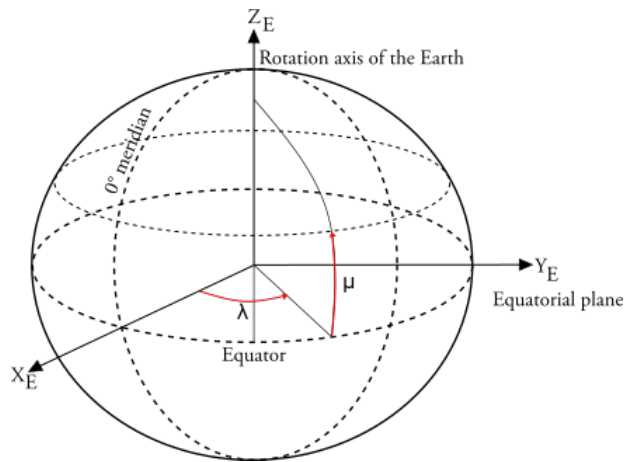


Figure 2.1: ECEF coordinates system [32].

World Geodetic System 1984

The World Geodetic System is defined by U.S. Department of Defense, and it's currently globally used revision is known as WGS84. The WGS 84 represents the standard physical model of the Earth used for the Global Positioning System (GPS) applications. This ellipsoidal model of the Earth's is based on a consistent set of constants and model parameters, which describe the Earth's size, gravity, shape and geomagnetic field.

The origin of the coordinate system coincides with the Earth's center of mass. The standard defines, that WGS 84 has a circular cross section at any given latitude. An ellipse with identical axes lengths for all longitudes is result after cross section through any meridian [32].

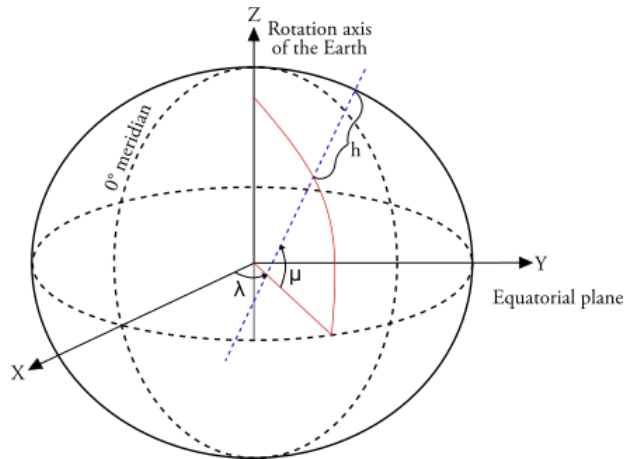


Figure 2.2: WGS 84 coordinate System.

Local North-East-Down system

The North-East-Down system is known as abbreviation NED. The NED is based on WGS 84. Its origin is arbitrarily fixed to a point on the earth's surface [32].

The NED convention specifies an x-axis that points to the north pole, a y-axis that points east and a z-axis that points perpendicular to the geoid surface. The z-axis is defined by the other two axes and its direction depends on the latitude and longitude of the origin of the NED frame. The NED coordinate system is also known as the navigation frame, which is centered in the aircraft, but it doesn't rotate with the aircraft because it remains at a local level [30].

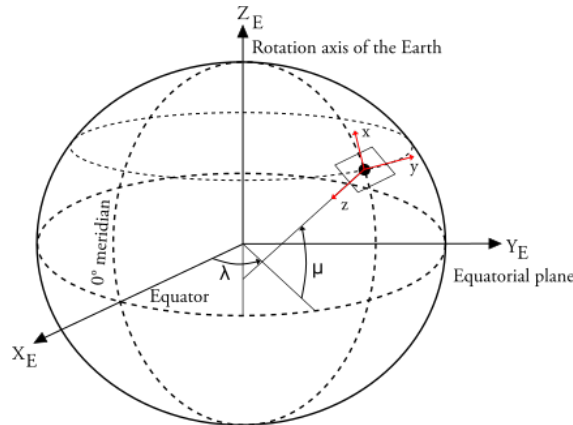


Figure 2.3: NED coordinate system [32].

Body Fixed Frame

The body-fixed coordinate system is a rotating reference frame with its origin fixed to the aircraft center of mass. The body coordinate system is directly defined on the body of the aircraft. Its axes are given by the following:

- the x-axis points forward from the center of gravity to the nose of the aircraft, lying in the symmetric plane of the aircraft,
- the y-axis points from the center of gravity to the right side of the aircraft,
- the z-axis points from the center of gravity to downward to comply with the right-hand rule.

An airplane can be maneuvered using the aerodynamic control surfaces, which change the amount of force that each surface generates. Depending on these forces, the aircraft rotates about a point known as a center of gravity. The center of gravity is given by the average location of the weight of the aircraft [32].

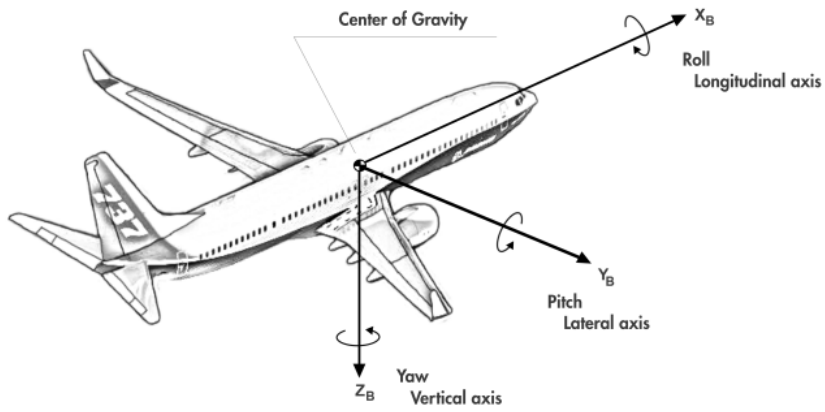


Figure 2.4: Aircraft rotations [36].

Aerodynamic coordinate system

The angle of attack is denoted by the Greek letter α and represents the aircraft-relative vertical angle between the centerline and the relative wind. The relative wind is defined as the velocity of the aircraft relative to the airmass through which it flies.

The angle of the sideslip is denoted by the Greek letter β and is defined as the aircraft-relative horizontal angle between the centerline and the relative wind.

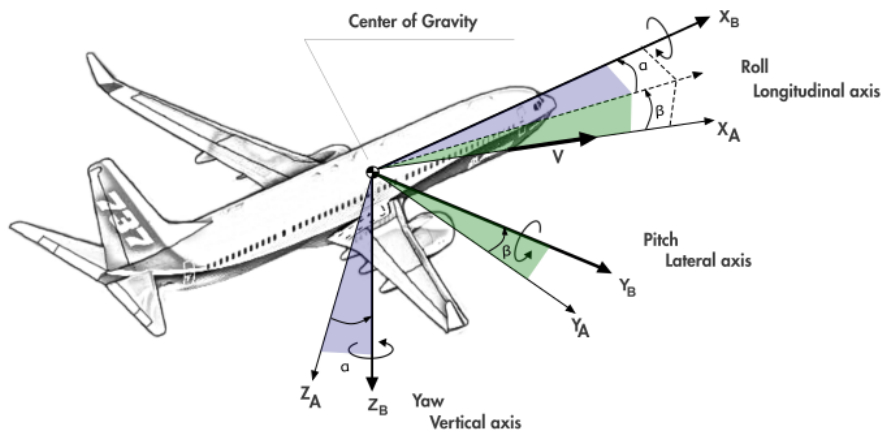


Figure 2.5: Aerodynamic coordinate system [36].

The true airspeed is denoted by V and represents the magnitude of the aircraft flight path vector relative to the surrounding air mass. The flight path vector points along the wind coordinate system x-axis. The true airspeed can relate directly to the ground

speed if the air mass isn't moving. Otherwise, it is necessary to include the velocity of the air mass relative to the ground to the ground speed.

Aircraft's aerodynamic forces and moments are determined by the orientation of the velocity vector with respect to body axes. The angle of attack and the sideslip angle express this orientation [33]:

$$\begin{bmatrix} V \\ \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \sqrt{u^2 + v^2 + w^2} \\ \arctan(\frac{w}{u}) \\ \arcsin(\frac{v}{V}) \end{bmatrix} \quad (2.1)$$

2.2 Angles between coordinate systems modeling

Leonard Euler introduced decomposition of this spatial rotation in the 18th century and thus the corresponding angles are called as Euler angles. Each rotation is about a single axis. Roll rotation (ϕ) is about x_2 axis, pitch rotation (θ) is about y_1 axis and yaw rotation (ψ) is about z_I axis. The three-angle rotation matrix is based on single-angle rotation matrices.

The Euler angles can be combined in the attitude vector [33]:

$$\Theta \triangleq \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} \quad (2.2)$$

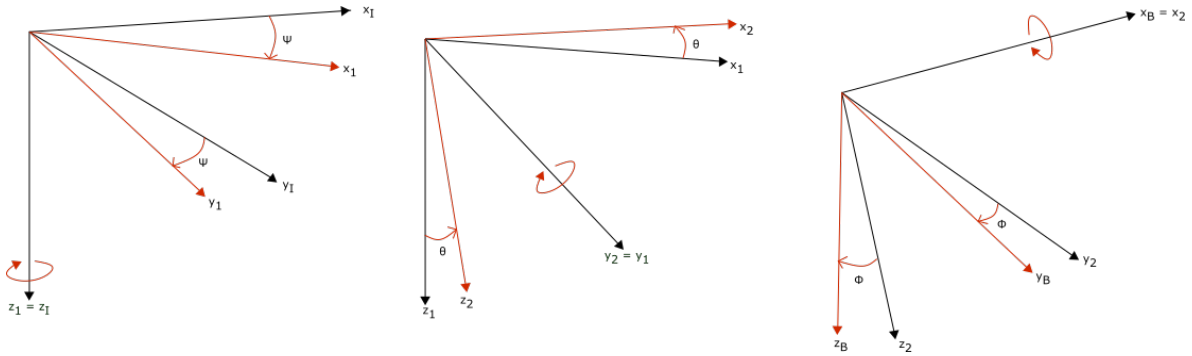


Figure 2.6: Transformation from NED to BFF.

2.2.1 Transformation between BFF and NED frame

The information in this section comes from [35].

For transformation between the BFF and NED coordinate systems, is needed to find a rotation matrix R_b^n . Euler angles aren't commutative and the rotations must be made in the specified order yaw, pitch, roll (zyx convention). This conventional sequence is also known as sequence 3-2-1. Each independent rotation is described by the following rotation matrices:

$$R_{z,\psi} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2.3)$$

$$R_{y,\theta} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \quad (2.4)$$

$$R_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \quad (2.5)$$

Based on this matrices it can be derived the rotation matrix from BFF to NED

$$R_b^n = R_{z,\psi} R_{y,\theta} R_{x,\phi} \quad (2.6)$$

$$R_b^n = \begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\phi + \cos\psi\sin\theta\sin\phi & \sin\psi\sin\phi + \cos\psi\cos\phi\sin\theta \\ \sin\psi\cos\theta & \cos\psi\cos\phi + \sin\phi\sin\theta\sin\psi & -\cos\psi\sin\phi + \sin\theta\sin\psi\cos\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \quad (2.7)$$

The calculated matrix gives the convention from BFF to NED. The transformation from NED to BFF is given by $R_n^b = (R_b^n)^T$, which gives

$$R_n^b = \begin{bmatrix} \cos\psi\cos\theta & \cos\theta\sin\psi & -\sin\theta \\ -\sin\psi\cos\phi + \cos\psi\sin\theta\sin\phi & \cos\psi\cos\theta + \sin\phi\sin\theta\sin\psi & \cos\theta\sin\phi \\ \sin\psi\sin\phi + \cos\psi\cos\phi\sin\theta & -\cos\psi\sin\phi + \sin\theta\sin\psi\cos\phi & \cos\theta\cos\phi \end{bmatrix} \quad (2.8)$$

where R is an orthogonal matrix

$$R_b^{n-1} = (R_b^n)^T = (R_n^b)$$

2.2.2 Quaternions

The information in this section comes from [34].

Euler angles disadvantage is that they can cause the problem of gimbal lock. Gimbal lock occurs when the axes of two of the three gimbals are driven into a parallel configuration. This problem causes the loss of one degree of freedom in a three-dimensional, three-gimbal mechanism. Quaternions provide a convenient mathematical notation for representing orientations and rotations of object in three dimensions.

In general form, a quaternion is an ordered list of four real numbers and it can be represented as vector

$$q = \begin{pmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{pmatrix} \quad (2.9)$$

Quaternion which represents a rotation must be a unit quaternion $\|q\| = 1$.

Early works by Hamilton presented the quaternion as having a scalar (S) and vector (\vec{V}) part.

$$S = q_0 \quad (2.10)$$

$$\vec{V} = (q_1, q_2, q_3) \quad (2.11)$$

For a rotation through the angle Θ , the scalar part of the unit quaternion is related to the magnitude of the rotation by

$$q_0 = \cos\left(\frac{\Theta}{2}\right) \quad (2.12)$$

The vector part is related to the axis of rotation by

$$\vec{V} = v \sin\left(\frac{\Theta}{2}\right) = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix} \quad (2.13)$$

Euler angles can be calculated from the quaternion as

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} \text{atan2}[2(q_0q_1 + q_2q_3), (q_0^2 + q_3^2 - q_1^2 - q_2^2)] \\ \text{asin}[2(q_0q_2 - q_1q_3)] \\ \text{atan2}[2(q_0q_3 + q_1q_2), (q_0^2 + q_1^2 - q_2^2 - q_3^2)] \end{bmatrix} \quad (2.14)$$

The corresponding quaternion elements for Euler angles are

$$\begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} \cos(\psi/2)\cos(\theta/2)\cos(\phi/2) + \sin(\psi/2)\sin(\theta/2)\sin(\phi/2) \\ \cos(\psi/2)\cos(\theta/2)\sin(\phi/2) - \sin(\psi/2)\sin(\theta/2)\cos(\phi/2) \\ \cos(\psi/2)\sin(\theta/2)\cos(\phi/2) + \sin(\psi/2)\cos(\theta/2)\sin(\phi/2) \\ \sin(\psi/2)\cos(\theta/2)\cos(\phi/2) - \cos(\psi/2)\sin(\theta/2)\sin(\phi/2) \end{bmatrix} \quad (2.15)$$

2.2.3 Transformation between BFF and Aerodynamic frame

Transformation matrix from Aerodynamic Frame to BFF:

$$R_{BA} = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos(-\beta) & \sin(-\beta) & 0 \\ -\sin(-\beta) & \cos(-\beta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2.16)$$

Transformation matrix from BFF to Aerodynamic Frame:

$$R_{BA} = \begin{bmatrix} \cos\alpha\cos\beta & -\cos\alpha\sin\beta & -\sin\alpha \\ \sin\beta & \cos\beta & 0 \\ \sin\alpha\cos\beta & -\sin\alpha\sin\beta & \cos\alpha \end{bmatrix} \quad (2.17)$$

2.3 Equations of Motion

The information in this section comes from [33].

Much of aircraft dynamics can be understood using mathematical models for the flat earth. The vector function represents 12 equations of motion with the benefit that the function evaluation can be an involved process.

2.3.1 Attitude differential equations

The attitude differential equations are given by:

$$\dot{\phi} = p + (q\sin\phi + r\cos\phi)\tan\theta \quad (2.18)$$

$$\dot{\theta} = q\cos\phi - r\sin\phi \quad (2.19)$$

$$\dot{\psi} = \frac{q\sin\phi + r\cos\phi}{\cos\theta} \quad (2.20)$$

2.3.2 Position differential equations

To determine the airplane's position, coordinates (latitude, longitude and altitude) in geodetic coordinate system are computed this coordinates:

$$\dot{\lambda} = \frac{\dot{Y}_{G_0}}{(N_0 + h)\cos\phi} \Leftrightarrow (V_E) \quad (2.21)$$

$$\dot{\phi} = \frac{\dot{X}_{G_0}}{M_0 + h} \Leftrightarrow (V_N) \quad (2.22)$$

$$\dot{\mu} = -\dot{Z}_{G_0} \Leftrightarrow (V_D) \quad (2.23)$$

2.3.3 Force equations

The forces are components of airplane velocity along its axis and the unit is meters per second ($m.s^{-1}$) [26]:

$$\dot{u} = rv - qw - g_0 \sin\theta + f_x \quad (2.24)$$

$$\dot{v} = pw - ru + g_0 \cos\theta \sin\phi + f_y \quad (2.25)$$

$$\dot{w} = qu - pv + g_0 \cos\theta \cos\phi + f_z \quad (2.26)$$

where f_x , f_y and f_z represents specific forces.

2.3.4 Moment equations

Moments are airplane rates along its axis. The unit is radians per second ($rad.s^{-1}$) [26].

$$\dot{p} = \frac{\sum L.I_Z + \sum N.I_{XZ} + pq.I_{XZ}(I_X - I_Y + I_Z) - pr(I_Z^2 - I_Y.I_Z + I_{XZ}^2)}{(I_X - I_Z - I_{XZ}^2)} \quad (2.27)$$

$$\dot{q} = \frac{\sum M - pr(I_X - I_Z) + I_{XZ}(p^2 - r^2)}{I_Y} \quad (2.28)$$

$$\dot{r} = \frac{\sum L.I_{XZ} + \sum N.I_X + pq(I_{XZ}^2 - I_X.I_Y + I_X^2) - qr.I_{XZ}(I_X - I_Y + I_Z)}{(I_X.I_Z - I_{XZ}^2)} \quad (2.29)$$

3. Historical overview

Technology around aircraft has changed dramatically over the past 100 years. The aim of this chapter is to give the reader a brief summary of this evolution. The evolution of civil and military aviation will be described in more details.

At first glance it may seem that there was a difference between development of the civil and the military aviation. However, this chapter shows that this development went together hand in hand. Until the World War I., aviation was perceived only as a hobby for privileged members of society the rich sportsman, but this was changed during the World War I, when the aircraft came into front-line in its new use as fighter. The history of instrumentation for flight data visualization can be divided into three technological eras:

- the mechanical era,
- the electromechanical era,
- the electro-optical era.

These eras are significant in terms of design changes [1] .

3.1 Mechanical era

Orville and Wilbur Wright (known as the Wright Brothers) were the first ones who were standing at the beginning of this era. The first flight of a heavier-than-air machine has taken place in USA since the brothers became interested in aviation, on 17th December 1903 and the aircraft (named as the Flyer) was flown by Orville Wright.

In their flying ventures, Wright brothers discovered that the important instrument to fly an aircraft is to provide a flight state visual representation. Until that time, the main instruments were only recorders of flight information. In Flyer, a few complement of instruments recorded flight data were used. All the instrument could be turned off by a wooden lever along with the engine.

List of used instruments: [2]

- anemometer - a mechanical device used to measure wind velocity,
- weather vane - measure the angle of incidence.

The first practical aircraft was developed after six years of their first interest in Aviation. The First World War has changed the view of the aircraft. Before that no significant development of aircraft has happened. During these years the airspeed indicator was added on the list of the basic instruments. This part of mechanical era is known as „The barnstorming years“. At the end of the First World War, semi-humorous manual about voice-operated aircraft features was released. The important thing is that this manual described the typical aircraft instruments at that time [1]:

- inclinometer,
- turn and slip indicator,
- magnetic compass,
- airspeed indicator,
- altimeter,
- watch.

3.2 Electromechanical era

In the electromechanical era, the aircraft development went forward. The main subject of this era was the standardization, as a lot of new information was needed to be shown on the flight deck. During this era, data displayed on the instrument panel were simplified for a better and a more intuitive orientation. A standard flight deck, known as the basic six, was created to display all of the most important flying instruments.

Avro Lancaster is probably one of the most significant bomber aircraft of the World War II. The very first Lancaster was flown in 1941. This aircraft was designed for long-range bombing and it was also the first aircraft with the basic six instruments layout. The basic flight instruments were selected considering the optimization for precision navigation. They included the airspeed indicator, gyro horizon, vertical speed, altimeter, direction indicator and turn & bank indicator. [1]



Figure 3.1: Avro Lancaster basic six layout [21].

As the aircraft performance has increased, the control of the aircraft itself had become more demanding for the pilots. For that reason, the U.S. Air Force made a special team consisted of engineers, pilots, and human factor specialist, with one important task to develop a complete instrument panel. After a while the USAF has introduced the Integrated Instrument Systems (IIS) referred as the basic T. The result of their efforts was a panel which displayed all the important air data.

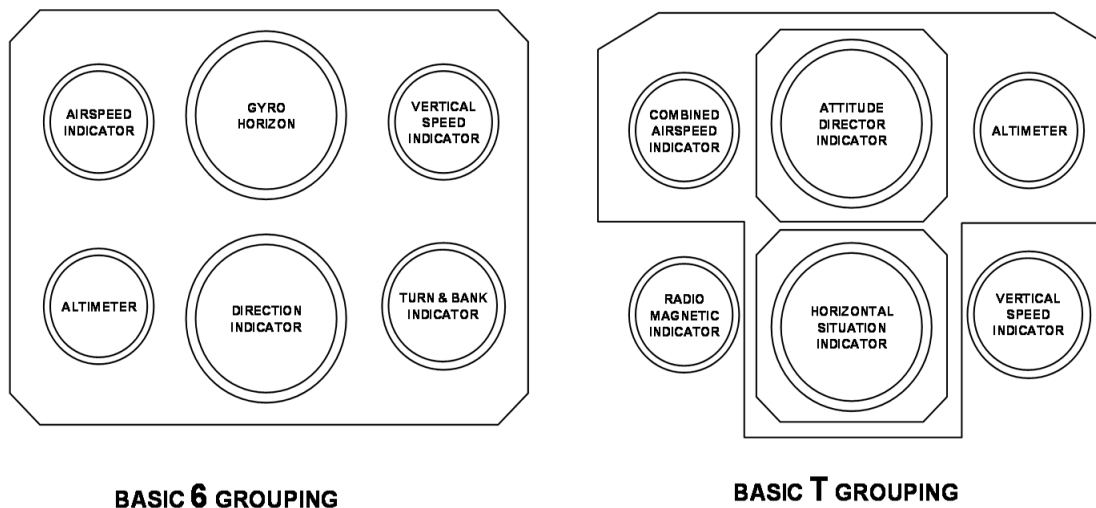


Figure 3.2: Cockpit layouts [15].

The basic T is composed of four instruments whose locations are fixed:

- Attitude Direction Indicator (ADI) - top centre,
- Horizontal Situation Indicator (HSI) - bottom centre,
- Airspeed Indicator (ASI) - top left,

- Altimeter - top right.

The Attitude Direction Indicator

The ADI combines the functions of three earlier basic 6 generation instruments into one:

- artificial horizon,
- ILS direction indicator,
- turn and slip indicator.

In the basic T, pitch was shown by attitude ball. The lower half was brown and represented the ground and the top half was blue and represented the sky. Bank angle, with a symbol of the plane in the middle, was placed in the bottom part of the instrument.

The Horizontal Situation Indicator

The HSI combines the functions of three earlier basic 6 generation instruments into one:

- compass (gyro and magnetic),
- radio magnetic indicator,
- distance measuring indicator.

Data which was originally displayed by a six instruments were now displayed by two instruments only. Remaining two free spaces were filled with the airspeed indicator and the altimeter.

The Altimeter

The altimeter displayed the barometric altitude using the pointer and the counter.

The Airspeed Indicator (ASI)

The airspeed indicator displayed the maximum safe speed, the actual speed and the Mach number [1].

3.3 Electro-optical era

As of 1970's the air traffic increased substantially. The cockpit display design which has been used since the electromechanical era still had some limits, but the change came with the design of the F-18. The F-18 is a multirole fighter which took-off for the first time in 1978. From the perspective of the cockpit display design it was a big step forward. The F-18 program can be considered to be the beginning of the Electro-Optical era.

New technology, known as the Cathode Ray Tube (CRT), was used for displaying the flight data. The reason why they have decided to use the CRT display was that the fighter aircraft is smaller so there is no space for a large flight deck. CRT technology is characterized by high flexibility design of displays and the ability to change display

To support the research needs, a ground base flight simulator was created. Six CRTs were installed to the simulator each with 6,,x4.5“ landscape usable screen area. The research focused on two areas of interest and also included pilots as human factor. One of this research areas was the variability of an all-glass flight deck and the other was decided to the side-by-side configuration of a Primary Flight (PFD) and Navigation (ND) displays. This layout has become practically standard today. [1]

4. State of the art

The current and future development depends on the type of the cockpit. Cockpits could be divided into two types:

1. the single/two seater combat aircraft cockpit,
2. civil aircraft cockpit.

The main development for military aircraft is happening right now. The future of the civil aircraft is radically different from the current development. The most advanced avionics researches are focused on:

1. integrating the pilot and the aircraft more comprehensively,
2. aircraft design and function,
3. aircraft construction.

In this time, cockpits have changed into information centers. Pilot receives massive quantities of data and he must determine the course of the action during a few seconds. However the truth is that today's pilots get a much more information than his colleague in the past. The simplicity which was the main topic during the entire evolution continues today [5].

4.1 Cockpit in civil aircraft

Current development is controlled by two largest companies for the production of civil aircraft. These companies are the Boeing and Airbus. Boeing has American origin and an Airbus has an European origin.

Boeing 787 Dreamliner

Boeing 787 Dreamliner is the latest and most advanced airplane made by Boeing. There is a new technology integrated but with considerable commonality with other airplane - Boeing 777. The 787 Dreamliner is equipped with a state-of-the-art flight deck.

It includes five big 12,9" displays in the cockpit. Together they are providing more space to display flight information. Large display in front of the pilot can display all flight information. One of the four other displays can also display these information.

Information can be input to the glass panel using number of buttons or also using a track pad to navigate the screen.

The 787 Dreamliner is delivered with dual HUDs. In the picture they are in stored position but otherwise they are in the pilot's line of vision. The primary flight display, which is in front of the pilot, displays important information including the airspeed, altitude, vertical speed, compass data and attitude indicator.



Figure 4.1: Boeing 787 cockpit and HUD [20] [17].

Airbus A350

The original A350 concept was changed according to the success of Boeing 787 Dreamliner. The cockpit is based on the A380 cockpit but includes additional improvements. There are six identical LCDs with 15.1" screen size. Maintenance costs have been reduced by using new technologies by up to 80%.

Beside the usual line-up, two displays were added (one for each side). The Onboard Information System (OIS) is shown on new displays by Electronic Flight Bag application from stowed laptops. A warning display was added to the bottom part of the PFD and the ND.



Figure 4.2: Airbus A350 cockpit [14].

Programmes like SESAR, NextGen and Clean Sky represent the potential of aviation industry. The SESAR consortium includes (Single European Sky ATM Research) companies like Airbus, Eurocontrol, Honeywell, Indra, NORACON and Thales. Last named, Thales Group, won a prestigious Red Dot Design Concept Award in 2013. This company was also included among Best of the Best award-winners. All these awards were won with Avionics 2020 cockpit [6].

4.2 Cockpit in military aircraft

Control of the aircraft is becoming the secondary activity for today's pilots. During a mission, there is a lot of things the pilot has to do. A big attention is given to the pilots on his visual abilities when observing unidentified aircraft with life data stream from the soldiers on the ground while communicating with his commander.

A long-term aim is to move the mission in front of the pilot. By using HUDs this aim is met partially. The most important information are in front of the pilot but he can not look anywhere else. Logical step is to move the displaying information on the helmets user. Modern fighter aircraft cockpits include:

- head-down display,
- head-up display,
- interactive control panels,
- instruments.

Eurofighter Typhoon

The Eurofighter Typhoon is a twin-engine, multirole fighter. The Typhoon was designed and is manufactured by a consortium of Alenia Aermacchi, Airbus Group, and BAE Systems. The project is managed by NATO Eurofighter and Tornado Management Agency, which they are also the prime customer.

The Typhoon features a glass cockpit without any conventional instruments. It comprise three full-color multi-function head-down displays (MHDDs), a wide angle HUD with forward-looking infrared (FLIR), a voice and hands-on throttle and stick, a Helmet Mounted Symbology System (HMSS), a Multifunctional Information Distribution System (MIDS), a manual data-entry facility located on the left glare shield and fully integrated aircraft warning system with dedicated warnings panel [28].

Boeing F-22 Raptor

F-22 Raptor is a single-seat, twin-engine, all-weather stealth tactical fighter aircraft developed for the United States Air Force. This aircraft is the result of the USAF's Advanced Tactical Fighter program. The F-22 Raptor was designed primarily as an air superiority fighter, but also has a ground attack, electronic warfare, and signal intelligence capabilities.

The F-22 Raptor has a glass cockpit with all-digital flight instruments. The monochrome HUD offers a wide field of view and serves as a primary flight instrument. This aircraft has also six LCD panels which displayed information. The USAF initially wanted to implement direct voice input (DVI) controls, but this was judged to be too technically risky. The integrated control panel (ICP) is a keypad system for entering communications, navigation, and autopilot data [27].



Figure 4.3: Eurofighter Typhoon cockpit (instrument panel)[16].



Figure 4.4: Locked Marting F-22 Raptor cockpit (instrument panel)[16].

5. Primary flight display

PFD in modern aircraft is much like multi-functional display and combined representations of older basic T. Even if layout is dependent upon manufacturer and installation most Primary Flight Displays are configured with a central AI and with IAS on the left side and ALT on the right side. Both of these indicators are usually presented as vertical tapes. Vertical deviation for ILS glideslope or VNAV (vertical navigation) is displayed to the right of the AI while lateral deviation from the ILS, VOR or FMS track is displayed below the AI. A compass reference is provided at the bottom of the instrument while, in most cases, flight director, approach, autopilot and auto-throttle modes are annunciated across the top of the instrument.

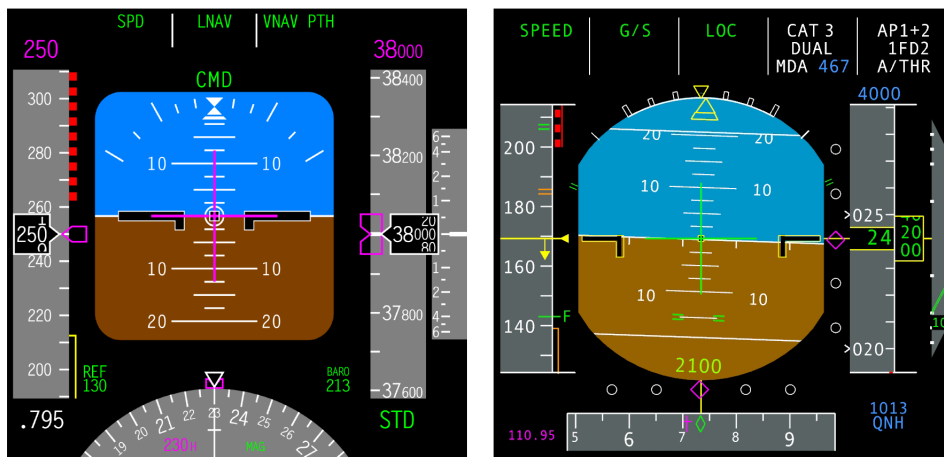


Figure 5.1: Boeing 737 and Airbus A350 PFD [22] [19].

6. User interface design

6.1 Motivation

Graphics design of the PFD was created with more futuristic appearance. At the beginning, the initial two graphic designs looked like a good idea but they would not fit for practical operation.

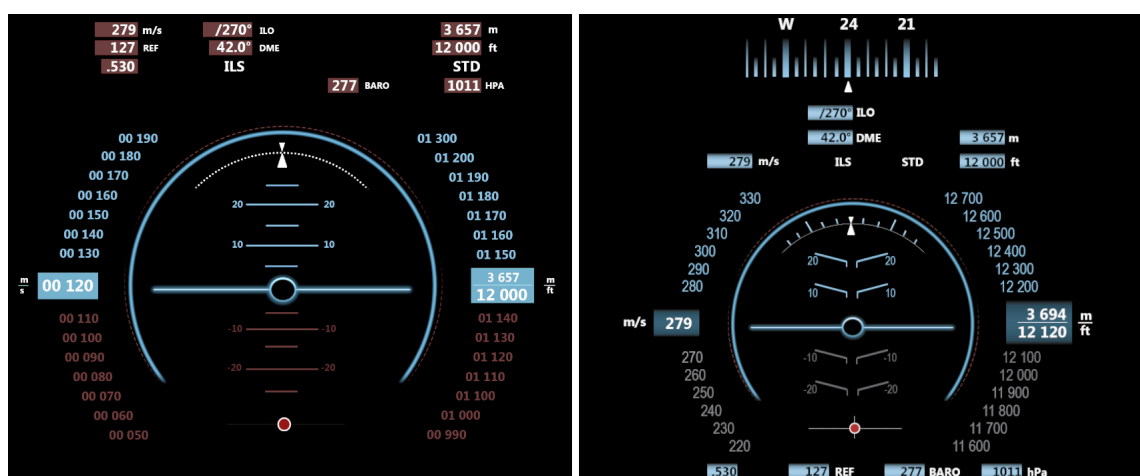


Figure 6.1: Proposals are at various stages of elaboration.

Third proposal of the graphic part was inspired by Human Factors and HUD researches. Next two subsections will summarize the main points of those researches.

6.1.1 Cockpit Design and Human Factors

High-stress levels and error rates are the results of complexity in instruments displaying aircraft systems. We can find few examples of problems like missed signals or misinterpreted information in the past which resulted in an aircraft crash.

Estimates in literature indicate that between 70 and 80 percent of aviation accidents can be partly attributed to human error (Shappell & Wiegmann, 1996). High stress levels and error rates are result of complexity of instruments displaying aircraft systems. There are few examples of problems which resulted in aircraft crash as missed signals or misinterpreted information.

Term “Human Factors”, covers all aspects of human involvement in aviation. According to Koonce Human Factors means:

“The study of the human’s capabilities, limitations, and behaviors and the integration of that knowledge into the systems we design for them with the goals of enhancing safety, performance, and the general well-being of the operators of the system” [23].

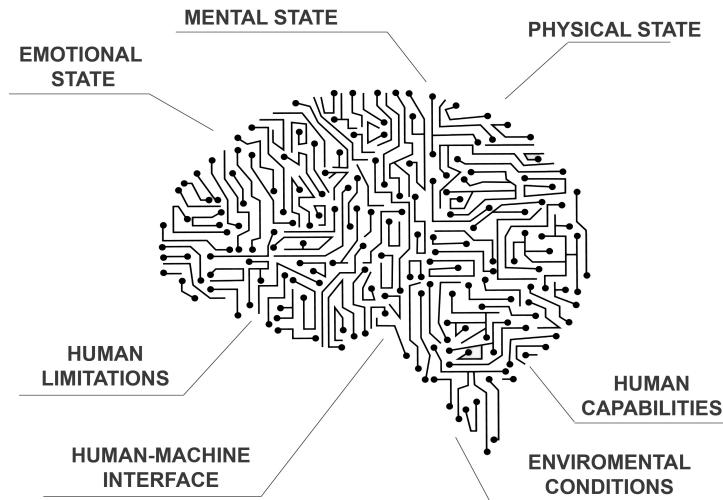


Figure 6.2: Human factors in aviation [23].

There are some design considerations for the cockpit as anthropometry or workspace constraints as:

- display and colors,
- shapes and colors,
- direction,
- warning system.

In fact, these things have an impact on human factors.

There are representative and informative functions on the display. In modern cockpit everything is designed around the design eye position. However due to workspace constraints essential but less prominent parts of the display will have lower priority over ones that are more prominent and frequent. Also it plays an important role to use the correct colors but it should be avoided to use too many different colors as it may cause confusion.

The main colors for system are:

- green - normal,
- amber/yellow - caution, flags and faults,
- red - alert or emergency.

Specification could not be follow as the goal is to keep futuristic design.

The recommendation is used for controls and levers but it is also useful for PFD. Arrows and shapes show size of pitch/yaw/roll of the aircraft. The most important aspect of any warning system is that it needs to be reliable. Aircraft warnings are shown with red color and serve one of the four following functions:

- Alert the crew of a problem,
- Describe the nature of the problem,
- Direct the appropriate actions,
- Provide feedback (is the problem fixed or does it still exist).

First idea was to notify warnings by blinking red alert. However this solution could be too stressful and it would be contrary to the recommendation which is saying that warnings should not be done in such a way that it will startle the crew or cause extra stress and workload. So the final solution is only red color for warnings [23].

6.1.2 HUD research

HUD research was inspired by TRISTAR studies which are focused on head-up display (HUD) symbology measuring pilot task performance. Practical part was conducted by NASA Ames Research Center by Tri-Service Flight Symbology Working Group (FSWG).

This study provide an instrument for exchange of information and ideas on flight symbology and test methods. Six experienced pilots were involved within four specific scenarios. Overall 14 variations were studied with respect to CDL presentation, CDM Quickening, airspeed and altitude positioning.

Pilots' responses were averaged and even when there were insufficient amount of records, a several interesting trends were revealed. The responses showed that pilots had mild preference for those characteristics:

- bent climb-dive ladder lines,
- vertical asymmetry,
- quickening.

Towards a Physiologically Based HUD (Head-Up Display) Symbology was the second research applied in this proposal. This research specifies what the ideal HUD symbology must contain. The main focus is on the structure of visual attention where the symbology has to be consistent with the three-dimensional structure of human attention. Global contour perception, preattentive cueing and visual-vestibular interactions in near vs. far visual space are next point research deals with [24].

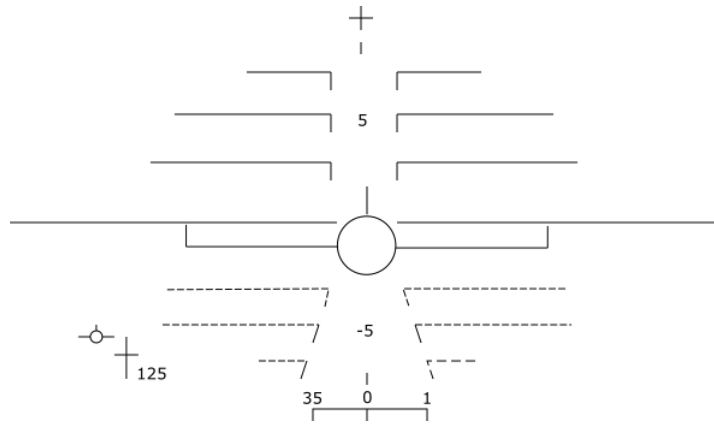


Figure 6.3: Full-format of prototype “physiological,, HUD display [24].

6.2 User Interface

Color selection was inspired by Sci-Fi movies where the futuristic technology was shown and the Photoshop graphic editor was used to create graphic design. The final decision is blue and yellow - for higher contrast, white and red for warning flags. It is also known that blue color has support in psychology when different shades of blue can improve concentration and stimulate thinking. That is the reason why blue color has been chosen as opposite for the red warnings as red color shows aggressive dominance.

Displayed data

Flight variables was chosen with respect to safety flight and specification. It includes the following:

- Airspeed [*kt*]
- Altitude [*ft*]
- Vertical speed [*ft/min*]
- Pitch angle [°]
- Roll angle [°]
- Yaw angle [°]
- Ground speed [*kt*]
- Mach number
- QNH [*hPa*]
- Angle of attack [°]
- UTC time (also known as Zulu)
- Duration of flight time
- Autopilot/Flight director setting

The flight data are displayed in a layout based both on the conventions and on a logical layout.

6.2.1 Display layout

The layout can be divided into three section and described in this subsection due to the overall impression. But it is necessary to mention that the data in the sections are to some extent intertwined.

Top section

Heading Indicator

The heading indicator is the only instrument that displays the current magnetic heading of the aircraft. The construction of the heading indicator enables to scan the rotation around the vertical axis of the aircraft.

The heading indicator is situated in the upper part of the display and it's displayed as a cylinder which rotates around the vertical axis. The flight direction is represented by the graphical representation and by the digital value. The current value of flight direction is displayed in a box with the heading pointer. The heading indicator is one of the three at which is displayed the bug. When the selected heading value is off the scale, the bug is parked at the left or right side of the heading cylinder. The pointer and the bug are vertically aligned when the current value and the selected value are equal.

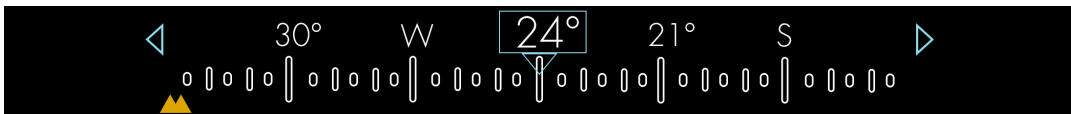


Figure 6.4: Heading Indication.

Flight Mode Annunciator

Below the heading indicator is displayed the Flight Mode Annunciator (FMA). The FMA displayed the names of autopilot functions that are armed. It is the only reliable source of information about what autopilot functions are in use. It contains three fields, one field for each function. The presented functions are SPD as airspeed, HDG as heading and ALT as altitude. Flight Mode Annunciator, selected values and bugs are related to the flight director, which will be described in the next subsection.



Figure 6.5: Flight Mode Annunciator.

Middle section

The middle section contains four basic aircraft instruments. These instruments include airspeed indicator, attitude indicator, altitude indicator and vertical speed indicator.

Attitude Indicator (AI)

The AI shows rotation about the lateral axis to indicate pitch, and about both the longitudinal axis to indicate the degree of bank. The principal parts of interest to the

pilot are the horizon bar, the miniature symbol of the aircraft and the degree marks on the upper periphery of the dial.

The horizon bar separates the AI on two halves of the grid. The upper half of the grid represents the sky and the second half of the grid represents the ground. Individual grid cells getting smaller from the top and the bottom of the display to the horizon line which evokes impression of three dimensional space. The aircraft is in level flight, when the wings of the aircraft are aligned with the horizon bar. The symbol of the aircraft is taken over from the HUD symbols. The pitch angle is represents by the line parallel to the horizon bar, which are labeled every 10 degree.

The bank attitude of the aircraft is represents by the roll scale, which specifics the bank angle 10° , 20° , 30° , 45° , and 60° . The triangle on the top of the scale is the zero index. This part contains also roll pointer and slip/skid indicator. The roll pointer indicates the direction and degree of bank. Precise bank angle can be displayed only by AI.



Figure 6.6: Artificial horizon.

Airspeed and Altitude indications

An airplane's speed is measured in knots and each airplane has its own specified airspeed that the pilot need to know because adherence to safe operating speed is imperative. The airspeed indicator works by comparing dynamic pressure and static pressure. Airspeed indications are computed using modern sensor technology on modern, computerized primary flight displays.

The altimeter is a sensitive barometer which measured air pressure and displayed it as a height, usually in feet above mean sea level (MSL). The altimeter must be set to the current barometric pressure adjusted to sea-level pressure to displayed an accurate height. Pilots can get the current altimeter setting from ATIS broadcasts, air traffic

controllers, and Flight Service Stations. When the barometric pressure is set properly, the altimeter shows the airport elevations before the take-off.

Airspeed and altitude indications are presented on vertical semi-circle tape on the left and right side of the attitude indicator. The values on both indications are displayed with the respect to the Boeing 737 Operation Manual which was published by the Boeing Company. The current airspeed and altitude are shown in the middle of the tape in the square selection. The units of the values are shown from the outside of the tape in the selections.

Both indicators have bugs that show selected altitude and airspeed for the autopilot. When the selected value is off scale, the bug is parked at the top or bottom of the tape and the moving range of the bugs is indicated by the line. The selected values in the digital representation are displayed above the tapes in the selected boxes.

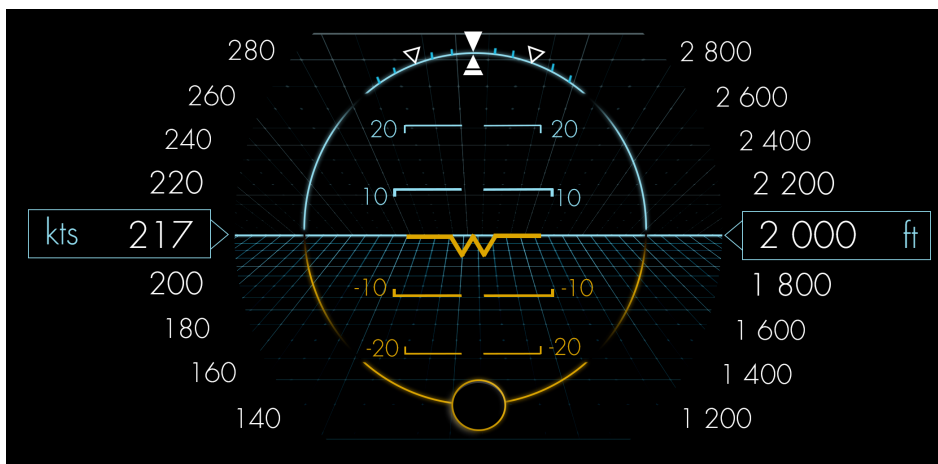


Figure 6.7: Airspeed on the left side and Altitude on the right side.

Vertical speed indicator

Vertical speed indicator is along the left side of the altimeter and shows the rate of the change of ascent in a number of feet per minute. This number is determined by changing the static pressure of the surrounding air. The pointer lags few seconds against the actual speed nonetheless it is more sensitive than the altimeter. The value is also presented digitally in the middle of the semi-circle. The vertical speed indicator is another element whose representation was inspired by the HUD symbology.

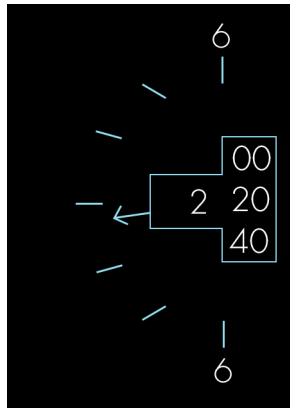


Figure 6.8: Vertical speed.

Bottom section

The bottom part of the display can be seen on figure 6.9.

Mach number and ground speed (GS)

GS indicates the actual speed of the airplane over the ground in one-knot increments. The GS can be detected by GPS or calculated from True Air Speed (TAS) and wind speed and direction. TAS represents the speed of the aircraft relative to the ambient air.

The ratio between the local speed of sound (LSS) and the TAS is known as the Mach Number in honor to Ernst Mach, who studied gas dynamics in a late 19th century. The ratio equals one when the TAS is equal to the LSS. Based on the Mach number it can be defined flight regimes in which compressibility effects vary.

Both values are displayed below the airspeed tape. The current Mach number is digitally represented when the airspeed increases above 0.4 Mach and it's blank when the airspeed decreases below 0.4 Mach [1]. The current GS value is displayed to the left of the Mach number when the airspeed decreases below 0.4 Mach. Both values are out of the convention and they're shown with the use of the blue color. Both values are shown with the use of the blue color to distinguish them from the airspeed values.

Angle of attack (AOA)

The angle of attack is denoted by the Greek letter α and represents the angle between the chord line of the aircraft's airfoil and the freestream velocity vector. The angle of attack is one of two variables, which can change the amount of lift generated by a wing. Wing produce the lift if the air flowing past an aircraft is aligned to the airfoil. This ensures a smooth airflow. If the value rises above the critical angle of attack the flow will break and the lift will drop sharply. The critical angle of attack is know also as the stall angle of attack and is defined as the maximum lift coefficient.

The current value is displayed digitally in degrees instead of radians. This representation is purely purposeful because the pilot has an immediate idea about the airplane tilt without unnecessary recalculation from radians.

Altimeter Pressure Settings

As outlined above, an ordinary airplane altimeter is basically a sensitive barometer, an instrument that measures air pressure. This is necessary to keep in mind because atmospheric pressure changes. If the pressure drops, the altimeter will show higher altitude even if it hasn't moved. This is the reason why the pilot needs to properly set the reference pressure to get correct altitude reading. The SI unit of measurement for barometric pressure is the hectopascal (hPa) and three different references are in common usage:

- QNH - Indicates the correct altitude above sea level. At the airport is shown the airfield elevation.
- QFE - If the QFE is set on the ground the altimeter show zero. If the QFE is set in the air, it will show the altitude above an airport.
- QNE - Also known as the standard pressure. When the standard pressure is set, it means that an aircraft altimeter indicates pressure altitude and is used by all aircraft operating above the transition altitude to provide a common datum for vertical measurement.

QNH and standard pressure are used on most flights. QNH is set for takeoff, low-level flight and landing. Standard pressure is 29.92 inches Hg/1013 hPa and all airplanes above 10,000 feet are requested to use this value.

The pressure setting is displayed on the right side of the screen. The current value is represented both digitally and by the semi-circle tape with the pointer. The pressure range is indicated by yellow part of the circle. When the standard pressure is set, the STD flag is displayed on the right side of the pressure circle. Otherwise is this place blank.

Time

UTC time and time of flight length are last two time data which are displayed in the fourth section. UTC is an abbreviation for Coordinated Universal Time and is defined as the primary time standard by which the world regulates clocks and time. UTC is sometimes known as Zulu time. It's because of the fact that the time zone using UTC is sometimes denoted by the letter Z. The Z letter is a reference to the equivalent nautical time zone (GMT) and word for Z is Zulu in the NATO phonetic alphabet.

Load factor

The load factor represents a global measure of the stress to which the structure of the aircraft is subjected and is defined as the ratio of the lift of an aircraft to its weight. The load factor is commonly expressed in g units because of the fact that an observer

on board an aircraft will experience an apparent acceleration of gravity to equal to load factor times the acceleration of gravity.

The graphic representation is designed as a circle with range -4 g to +5 g. Extreme values are marked with the red mark. The current value is represented both digitally and the pointer. The current number is displayed in the middle of the circle and pointer is moved to the right position on the circle. This solution provides a clear visual feedback to the pilot about his possibilities in view of the extreme values.



Figure 6.9: Display without Flight Director.

6.2.2 Autopilot/Flight director

The main section for displaying Flight Director/Autopilot setting. The Flight Director is related to the autopilot system and can be displayed independently on the Autopilot. It displays a guide on the artificial horizon, which shows the attitude of the airplane. The flight director does nothing to control the plane so the pilot can manually fly the plane directly where the flight director indicates. Simply put, the guide represents a reference of an airplane attitude that will follow the parameters set for the autopilot.

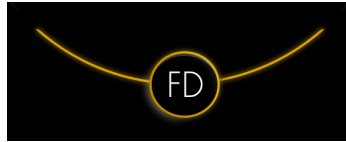


Figure 6.10: Flight Director indicator.

Autopilot flies the plane to follow the Flight Director, if the autopilot is engaged. The Flight Director serves as a visual indication of where the autopilot wants the plane to go. When the pilot wants to engage Autopilot, he must first turn on the Flight Director. The Flight Director will show where the autopilot wants the plane to be, and then to engage the Autopilot, which will then automatically fly the plane.

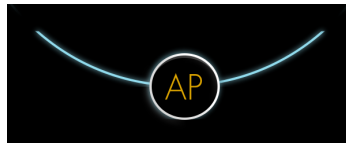


Figure 6.11: Autopilot indicator.

The contrasting yellow color is used when rendering an element based on the flight control setting. If an aircraft is driven by a pilot, this color is primarily used for rendering the element at the bottom of the display and the lower part of the artificial horizon which indicates ground. In the case of autopilot activation, the pilot has a minimized need to monitor this data. Therefore, the non-autopilot display sections are blue and the yellow color is used for displaying the autopilot sections which includes selected airspeed, altitude, heading and a lock for this selected data.



Figure 6.12: Display with Flight Director.



Figure 6.13: Display with Flight Director and Autopilot.

7. Implementation

This chapter describe the structure and implementation of the application. The implementation solution is composed of two parts:

- rendering scene,
- getting data from simulator.

The following part of the thesis is divided into two sections. The first section describes tools which were used in the implementation. The text is focused on basic functionality description and the possibility to use. Alternative tools are shortly described in some cases. The following section describes implementation details of rendering scene, data processing, and network communication interface.

7.1 Tools used

The tools used include a graphic library, extension library for interaction with windows and fonts, graphic editor, simulation environment, a simulation environment for obtaining data and communication protocol.

7.1.1 OpenGL

OpenGL (Open Graphics Library) is widely used standard in the industry. This library was developed by Silicon Graphics Inc. and it was released in January 1992. OpenGL is a cross-platform and cross-language API (Application Programming Interface). For that reason, OpenGL is purely concerned with rendering without APIs for input, audio, or windowing.

It is environment for developing portable 2D and 3D graphics applications. The API is typically used to interact with a GPU (graphics processing unit), to achieve hardware-accelerated rendering. The API is designed to be implemented mostly or entirely in hardware and is defined as a set of functions which may be called by the client program. Definition of these functions are similar to those of the C programming language.

Many industries and companies use OpenGL for these reasons for their applications. Among these applications belongs [\[45\]](#).

Aviation industry

Honeywell - display and graphics systems for airplane cockpits

Game industry

Laminar Research - X-Plane simulator

Rovio Entertainment - Angry birds for PC and Android versions

EA Games, Aspyr - Medal of Honor

Medical industry

CTI (Renato Archer Information Technology Center) - InVesalius is a software used to generate virtual reconstructions of structures in the human body

Another applications using OpenGL

Scilab - mathematical tool

Blender - animation, game engine and 3D CAD

Google Earth - earth mapping

Adobe After Effects - digital visual effects, motion graphics, and compositing application

FreeGLUT

FreeGLUT is an open source alternative to the GLUT library which is a abbreviation to OpenGL Utility Toolkit. FreeGlut contains functions for event processing, creating GUI and for working with windows including opening, resizing and cancellations just like GLUT. Since GLUT development is in stagnation, FreeGLUT is in development to improve the toolkit and has only a few differences [44].

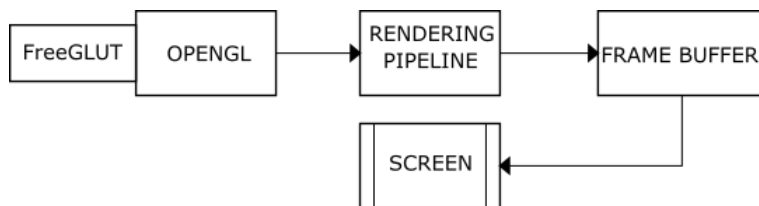


Figure 7.1: Procedurally generated rendering scenes.

7.1.2 Photoshop

Adobe Photoshop CC 2015 is a raster graphics editor developed by Adobe Systems for macOS and Windows. Since 1988, when it was created, it has become the industry standard in raster graphics editing. It can edit and compose raster images in multiple layers. It can also support masks, several color models including RGB (red, green, blue), CMYK (typically used for color printing - cyan, magenta, yellow and black as key), Lab color space, spot color and duotone and alpha compositing.

Photoshop uses its own PSD and PSB file formats but it has support for graphic file formats including PNG, JPG and JPEG. It was used CC 2015.1.2 version for creating some of the symbols [40].

As alternative to Photoshop can be used GIMP. GIMP is abbreviation for GNU Image Manipulation Program and it is a cross platform image editor available for OS X, Windows, GNU/Linux and another operating systems. It is a free software so users can change its source code and distribute it. Drawing also supports layers and layer masks. GIMP has support for indexed colour and RGB color spaces. Gimp uses XCF (eXperimental Computing Facility) file format which is designed to store all information it can be contained about an image. This tool has also support for BMP, JPEG, PNG and other file formats [42].

7.1.3 Microsoft Flight Simulator

Microsoft Flight Simulator is simulation program for the Microsoft Windows. It's one of the most comprehensive flight simulator programs on the market. The latest version was named as Flight Simulator X (FSX) and it was released in 2006 in Standard, Gold and Deluxe editions. FSX was chosen for three main reasons. The Deluxe edition contains software development kit (SDK), the existence of a huge user base and possibility to use FSUIPC add-on for getting flight data.

Microsoft ESP

ESP is a set of tools that enables simulation of real-world objects for educational purposes and SDK can be used to create add-on components for it. These components include new aircraft models, instruments, building and other structures as well as new missions such as tutorials and test of skills and knowledge. SDK components are divided into four kits [41]

- core Utilities kit,
- environment kit,
- mission Creation kit,
- simObject Creation kit.

The Core Utilities kit include SimConnect SDK, which is the programmer's interface to ESP. This SDK allows programmers to implement a custom interface for receiving flight data.

7.1.4 FSUIPC4

The FSUIPC (Flight Simulator Universal Inter-Process Communication) is an utility developed by Pete Dowson. FSUIPC4 version is designed for FSX and it's build on SimConnect. This utility allows external applications to access FSX internal variables include pitch, roll, altitude, weather and more. All values are placed in offsets, which are the memory blocks at a certain location. The FSUIPC reserves a 65535 byte block

of memory and then populates part of this memory with various pieces of data extracted from FSX [43].

7.2 Runtime

Runtime is controlled by WINAPI WinMain function and it's composed of several steps which is shown in figure 7.2. OpenGL attempts to create a window after the start of the application. In case of success, window is displayed. The following part runs in the loop until the application is terminated.

Then is the program run divided into two threads. In the first thread will be realized the connection with the server and the data will be prepared. The data will be prepared after the connection with the server will be realized. This process will be realized in the first thread. Along with this thread will run the second thread, in which will be loaded the textures and the positions will be precalculated for rendering some elements on the scene. This step is done for the optimization purposes. It is necessary to determine the position of some elements using arithmetic operations, which includes trigonometric operations.

Based on this data the scene will be rendered in the loop. This process will be controlled by CreateGLWindow function, which catches handlers and messages for the window and detects if the window is still active. Last mentioned function was used during debugging.

The program can be ended using the Escape key or using the Cancel button in the top right corner in the window. This action will cause termination of both threads. This will be released all allocated resources, closed window and terminated communication with the server.

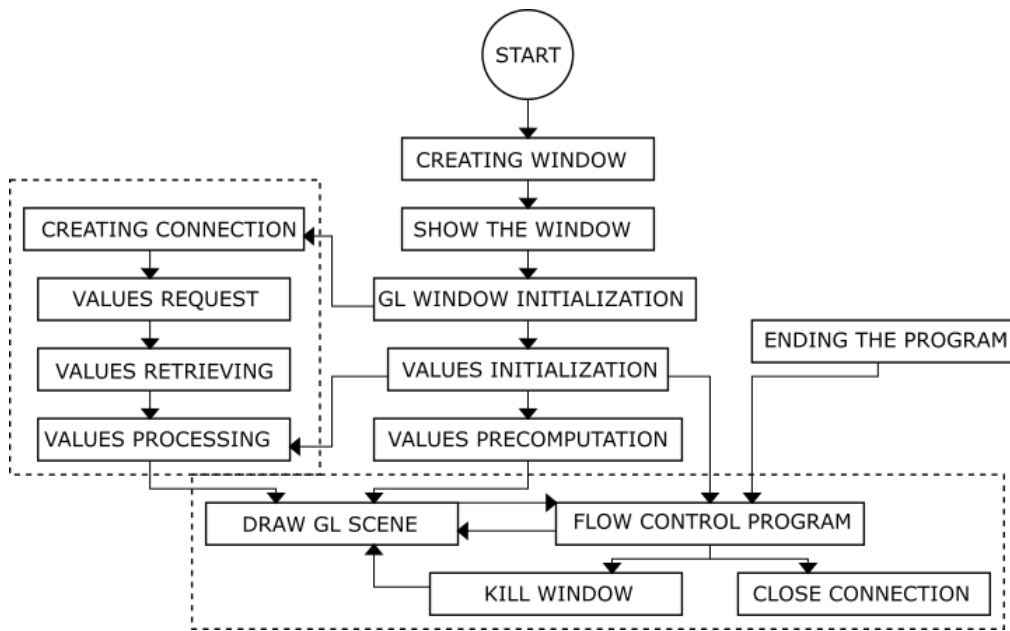


Figure 7.2: Runtime diagram.

7.3 Scene rendering

C++ language was used for implementation and the scene rendering is realized using OpenGL which was described as tool in previous section.

Syntax for most of the functions declared in OpenGL is used quite cleverly. Function name can be divided into four sections, where each section indicates important information about the function. This system can be described at simple function:

```
glColor3f(1.0, 1.0, 1.0);
```

Function name begin with gl prefix. Every OpenGL function begins with this prefix. Some of the extension libraries use the same principle. GLUT library used glut as the prefix. Body of the function name is followed by prefix which mostly indicates created object or function property. Number of parameters is indicated by the digits behind the function body. Function with zero parameters haven't any digit on this part. Data type of parameters is described by one or two characters in the end of the function name.

Graphical primitives

Each realistic and complex models are simple triangles and pixels. OpenGL is referred as a low-level API because of its minimal support for higher-order primitives. OpenGL focuses on rendering low-level primitives efficiently and with variety of basic, yet flexible, rendering features. OpenGL provides ten different primitive types for drawing, which are divided into three categories. They are points, lines and polygons. Implemented

solution used only some of this primitives.

- `GL_LINES` - OpenGL draws a line segment for each group of two vertices.
- `GL_LINE_LOOP` - OpenGL draw this primitive as line segment between each two points as they go behind.
- `GL_TRIANGLES` - triangle is rendered for each group of three vertices.
- `GL_TRIANGLE_STRIP` - this primitive is drawn as a sequence of triangles that share edges.
- `GL_QUADS` - this primitive is drawn as individual convex quadrilaterals for each group of four vertices.

The various compilers and environments have their own rules for the size and memory layout of various C variables. To make it easier to transmit OpenGL code between platforms, OpenGL defines its own data types. These data types corresponding C data types under the Windows 32-bit environments. OpenGL data types have also `gl` prefix and include `GLshort`, `GLint`, `GLfloat`, `GLdouble` etc.

Textures

Some sections of the scene was rendered using bitmap images. Bitmaps are defined as a regular rectangular mesh of pixels, each pixel containing a color value. The bitmaps are characterized by two parameters, the number of pixels and the color depth per pixel. To bitmaps can be applied other attributes but they are derivations of these two fundamental parameters.

Bitmap image file format is a one of the well known raster graphic file format. BMP allows to store image pixels with maximum 24 bits color depth per pixel. Because of the need to work with the alpha channel it was used a TGA (Truevision Graphics Adapter) format. The TGA format allows to store the data with 32 bits of precision per pixel with the maximum 24 bits of RGB and extra 8-bit alpha channel.

Characters rendering

Bitmaps font was used for text rendering in the beginning of the implementation. This solution has one simple problem. The bitmaps are binary images in OpenGL that means that an OpenGL store only one bit of information per pixel.

GNU FreeType library was used for rendering better looking fonts. FreeType is the same library that Blizzard uses to render the fonts in their games. Another products that uses FreeType library, either exclusively or partially are iOS, Android and ChromeOS. This library uses a fair number of gray pixels around the edges of the text. This is typical anti-aliased because the font looks much smoother from a distance.

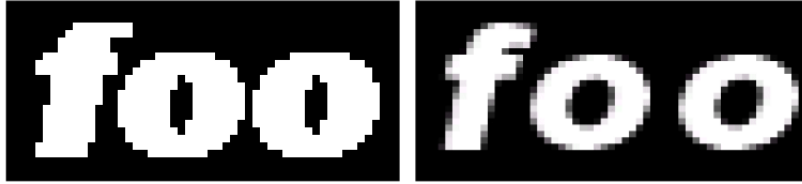


Figure 7.3: WGL and FreeType bitmap font [39].

Network communication

Network communication between application and the simulator is based on TCP/IP model. TCP/IP (Transmission Control Protocol/Internet Protocol) uses the client-server model of communication. There are two main protocols at transport layer which can be used. These protocols are TCP (Transmission Control Protocol) and UDP (User Datagram Protocol). Both protocols working with the IP (Internet Protocol), which defines how computers send packets of data to each other.

UDP used for establishing loss tolerating and low-latency connection between applications. UDP works on a simple principle when protocol just sends the packets. It means that it has much lower bandwidth overhead and latency. However packets can be lost or received out of order due to the different paths individual packets traverse between sender and receiver.

TCP has higher latency and additional data overhead, but this is caused by additional services. TCP has services for breaking large data sets into individual packets, reassembling packet into the correct sequence and checking and resending lost packets.

Both protocols need to know port number and destination IP address to establish the connection.

8. Testing

Software testing is an important part of a development. The aim of this chapter is describe testing process both during implementation and in the final phase of the project.

8.1 Unit testing

Individual functional blocks were tested during the implementation with the use of temporarily implemented function which detected press of a key. Keyboard keys were assigned to the flight variables with the options to increment or decrement value of these variables. The operating system provides language-independent keyboard support by using a language specific keyboard layout currently selected by the user or the application. This was solved with use of virtual-key codes used by the system where the wParam parameter of a keystroke message contains the virtual-key code of a key that was pressed or released.

Connection to the simulation environment was the next step of the testing. For this purpose was selected the FSX simulation environment, which is described in the chapter 7.1.3. The FSUIPC protocol was used to obtaining the flight data. A more detailed description of the protocol is in the chapter 7.1.4.

Both applications were ran on the same device and they communicated using localhost. This method was implemented in addition to the method described above, so the program was able to respond to both to keystrokes and to the FSX data in independent on true/false setting of a testMode variable.



Figure 8.1: Testing in simulation environment.

Testing is divided into the following areas:

- Displaying elements on the correct position.
- Reaction to the activation of the flight director and autopilot.
- Behavior of the elements for standard data.
- Behavior of the elements for maximum and minimum values.
- Behavior of the elements for maximum values + 1 and minimum values - 1.
- Readability of the display during different conditions.

Element display on the correct positions has been reviewed and edited quite often during the implementation. Attention was put on verifying the correctness of the display of the individual elements on the scene both in a idle mode and during motion and rotation. Particular attention was paid to displaying the text. Position of the numerical values had to be adjusted in depending on number of digits.

Testing of the fifth item of the list was carried out using keys. The value was set on the lowest possible and then it was decremented for a several times. This process was an opposite for testing the value beyond the limit for the highest possible.

8.2 Laboratory testing

Testing was carried out in the AW737NG laboratory at the Faculty of Information Technology, Brno University of Technology. In the laboratory, the simulation environment consists of two computers. On one of the computers is installed the simulation core the Microsoft Flight Simulator X to which the three projectors are connected. These projectors mediate the graphic output from the simulation. The second computer is hidden behind the dashboard in the cockpit and the implemented application run on it. The graphical output from the application is displayed on the two of three monitors, which are connected to the computer in the cockpit.

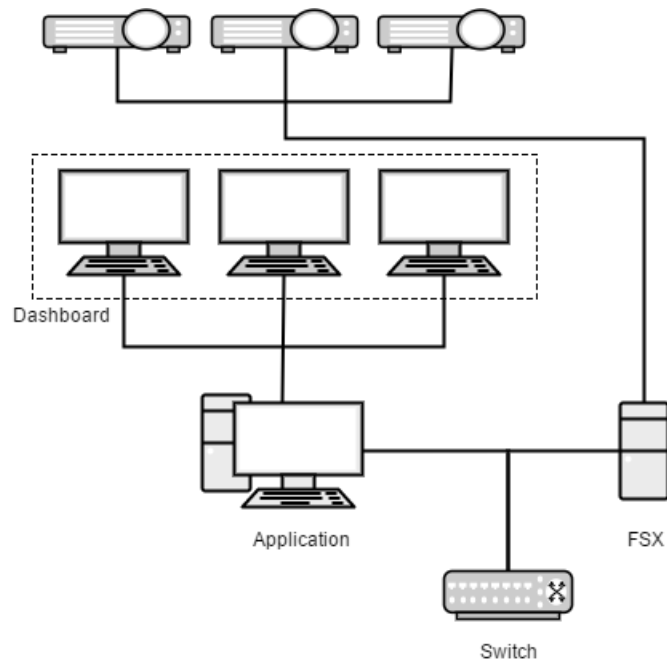


Figure 8.2: Wiring diagram of the simulator.

Communication between the FSX and the application is executed using the WideFS which is a network application interface for FSX. This interface allows external application to read values from FS and write values back.



Figure 8.3: AW737NG simulator.

Deploying the application to the simulator has brought a number of minor problems, especially in the screen size. The screen size was reduced from its original size 650 x 650 pixels to a more suitable size 630 x 630 pixels. Following this change, it was necessary to edit the position and size of the elements.



Figure 8.4: Display layout on the dashboard.

The final part of the testing is known as usability testing. This technique is used to evaluate an application by testing it on users. A method used in this case is referred to as moderated in-person, which means that a facilitator is co-located with the participant. One of the most common usability tests is a problem discovery test. A small group composed of experienced and inexperienced users was involved into this test [37].

The AeroWorks team from the Brno University of Technology was approached for getting feedback from more experienced users. The inexperienced users were chosen from among students from faculties of FIT, FEKT, and FSI. Each test participant was entrusted with the role of a pilot or a co-pilot. Test case consisted of take-off, few minutes flight, and landing. After completing the test case, each user filled out a prepared questionnaire. The pattern of the questionnaire is included in the annex.



Figure 8.5: Usability testing.

The test results demonstrated to achieve the main goal of this work. All test participants evaluated the overall impression of the application graphical appearance with a maximum of points. Unfortunately, concerns about sufficient font readability have been confirmed. With this result was already taken into account during the implementation phase, and therefore it was implemented the ability to change the font with small modification in the code. The second problem was recorded in the readability of the vertical speed indicator.

9. Future Development

Future development of the application could be inspired by the current direction of development in the aviation industry. The aim of this chapter is to give a short report about this trends.

Thales's Avionics 2020

Avionics 2020 is symbol of next generation cockpit from Thales. Thales put together a team of experts composed of pilots, scientists, engineers, psychologists, doctors and world-class experts in the field of human-machine interfaces. Hardware and software interactions are in new cockpit in accordance with look-and-feel perspective.

Avionics 2020 uses ODICIS (One Display for a Cockpit Interactive Solution) conception. Thales expects that this conception becomes standard for commercial aircraft in next 20. years. List of uses innovations:

- I4D (Initial 4D) Trajectory - Combines air and ground operations in three dimensions and with time.
- D-Taxi (Digital-Taxi)up-link - Warning system for air traffic control.
- ASAS (Airborne Separation Assistance Systems)- Tool for helping flight crew predict conflicts to.
- ECO Take-off - Compromise between CO2 emissions and noise reduction at takeoff and climb [11].



Figure 9.1: Avionics 2020 cockpit [13].

ALICIA research

ALICIA is a research and development project co-funded by European Commission under the Seventh Framework Programme. ALICIA aims at developing new and scalable cockpit applications which can extend operations of aircraft in degraded conditions. ALICIA research combines the latest thinking in air traffic management (SESAR) with new cockpit concepts capable of providing improved mission performance whilst also enhancing situation awareness. This research is focused on the two key areas of technological advance:

- All Condition Operations (ACO) system capable of delivering robust worldwide operations capability, allowing aircraft to use airports with less capable ground based approach aids, in a wider range of degraded flight conditions.
- A new cockpit architecture facilitating the introduction of new cockpit technologies and applications capable of driving down crew workload whilst enhancing safety and improving crew situational awareness.



Figure 9.2: New cockpit concept [29].

10. Conclusion

This bachelor's thesis deals with the design and implementation of a primary flight display application for flight simulator. It contains the description of research in human factors and symbols on the Head-Up display, on which the appearance of the application is based. The color scheme of each element of the display changes depends on activation of the Flight Director or the Autopilot.

The application was deployed and tested on the school simulator located at the Faculty of Information Technology of the Brno University of Technology.

There are several options for potential application extension. A terrain based on the data from height maps can be rendered. The idea is that terrain would be displayed at the altitude less than 6000 feet. If the altitude would be higher, the already implemented mode would be displayed.

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Appendices

List of Appendices

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A. Content of the DVD

An enclosed DVD disc contains following:

- this document in pdf format,
- latex source files of this document,
- directory with application source codes,
- directory with textures,
- directory with executable file and .dll libraries.

B. PFD - basic mode



Figure B.1: Display with Flight Director.

C. PFD - active Flight Director



Figure C.1: Display with Flight Director.

D. PFD - active Autopilot



Figure D.1: Display with Flight Director and Autopilot.

E. Questionnaire

Finální dotazník

1. Věk: 20 – 30 30 – 40 40 – 50 50 a více

2. Máte zkušenosti s leteckým simulátorem?

Ano Ne

3. Vlastníte pilotní průkaz?

Ano Ne

4. Uveďte počet nalétaných hodin, pokud tento údaj existuje: _____

5. Čitelnost písma:

	1	2	3	4	5	6	
Nedostatečné	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Vynikající

6. Jsou všechny prvky jasně viditelné?

Ano Ne

7. Celkový dojem:

	1	2	3	4	5	6	
Nedostatečné	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Vynikající

8. Splňuje vzhled aplikace Vaši představu futuristického designu?

	1	2	3	4	5	6	
Nedostatečné	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Vynikající

9. Co byste změnili nebo doplnili?
