Design and Integration of a Tilt-Rotor Flight Simulation Platform

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ABSTRACT

This paper introduces a tilt-rotor flight simulation platform for research and teaching purposes implementing a real-time simulation of the Bell XV-15 aircraft. The mathematical model of the XV-15 aircraft has been implemented including simplified models for the aerodynamics of the whole aircraft, rotors, and engine dynamics. Hence, the simulation is performed in a graphic environment to reproduce the simulated flight and to interact with it using commands given by the pilot. The simulation platform is implemented using MATLAB/Simulink®, while the input commands are set using USB peripherals, i.e., a flight stick and a pedal board. Instead, the visualization environment is performed using FlightGear, an open-source and cross-platform software that is widely used in research. The result is a portable tilt-rotor simulator to be executed on a commercial pc, while ensuring real-time performance. The tilt-rotor flight simulator is also validated by a licensed helicopter pilot returning positive feedback regarding the flight experience.

NOTATION

EoM	Equations of Motion
FCC	Flight Control Computer
GTRS	Generic Tilt Rotor Simulator
PFD	Primary Flight Display
SCAS	Stability Control and Augmentation System
UAM	Urban Air Mobility
VTOL	Vertical Take-Off and Landing

INTRODUCTION

Thanks to their unchallenged low-speed maneuverability and vertical take-off and landing capabilities, helicopters still play a crucial role in many civil and military operative scenarios. On the other hand, the concept of Urban Air Mobility (UAM) is pushing toward the development of a wide range of innovative VTOL (Vertical Take-Off and Landing) aircraft architectures that may enhance the transport of people and good in high population density areas.

Tilt-rotor aircraft are unique thanks to their hybrid configuration and flexibility. A tilt-rotor can convert its nacelles within a range of 90 degrees and over from the helicopter mode (performing a vertical take-off and landing) to the airplane mode providing enhanced vehicle's performance in terms of speed, endurance and fuel consumption (Ref. 1). For these reasons, the tilt-rotor concept became popular for the development of innovative and high-performance aircraft both in commercial and civil platforms, as well as drone applications (Ref. 2).

The tilt-rotor configuration began to attract interest in the 1970s thanks to the Tilt Rotor Research Aircraft (TRRA) XV-15, a joint development of NASA and Bell Helicopter Textron (Ref. 3). In the last years, several tilt-rotor aircraft have been already studied, especially for the development of a new generation of aircraft for the UAM to provide several applications such as air taxi, search and rescue and transportation to name a few (Ref. 4).

However, such innovative and unconventional platform is no without problems that limit its performance (Ref. 5). The considerable wing download caused by the flow stream of the rotors in helicopter mode, the tilting mechanism which allows the conversion of the rotors during flight, the behavior of the wing in backwards flight and the coexistence of both conventional aircraft and rotorcraft flight controls are some of the main problems concerning tilt-rotor aircraft, compromising the in-flight stability and maneuverability. For these reasons, the development of a suitable and reliable flight simulator is essential for the development of such hybrid configuration (Ref. 6).

Flight simulators allows to reproduce a virtual environment in which an aircraft is reproduced according to the mathematical

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Presented at the Vertical Flight Society's 78th Annual Forum & Technology Display, Ft. Worth, TX, USA, May 10-12, 2022.

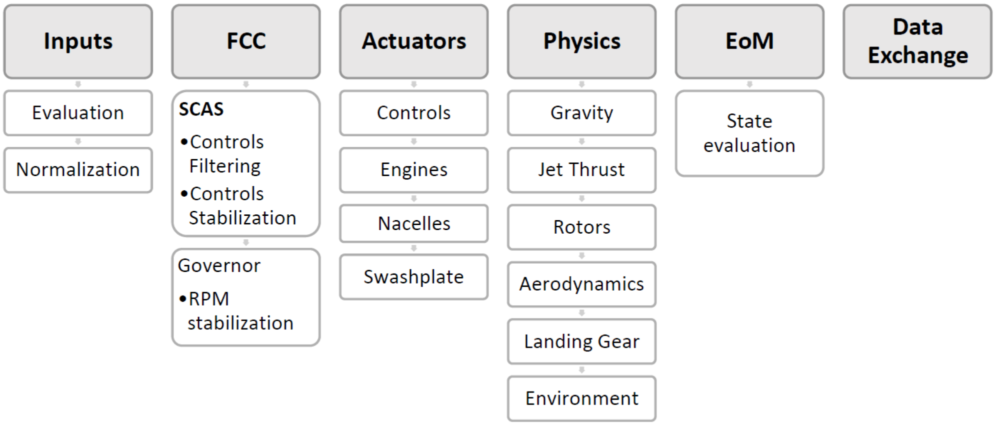


Figure 1: the structure of the proposed Tilt-Rotor Flight Simulation Platform

equations that govern the flight dynamics, the dynamics of the flight control system, but also the environment (Ref. 7). The development of a suitable flight simulator leads to several advantages in terms of safety and costs, as well as making a useful tool for training, research, and teaching.

In the literature, several works have been proposed on tilt-rotor simulation models especially related to the Bell XV-15 and the Bell Boeing V-22 Osprey (Refs. 6, 8, 9). One of the most important studies has been presented in Ref. 10, in which a generic tilt-rotor model for real-time flight simulation is proposed developing the so-called Generic Tilt Rotor Simulator (GTRS). In Ref. 11, the model is enhanced by reporting the last issue of the GTRS model available on public domain. In recent years, the GTRS has been used as baseline for the development of new tilt-rotor mathematical models in Refs. 1, 12 and 13.

Regarding the tilt-rotor simulation model, a big effort has already been made by our research group. In Ref. 14, the GTRS mathematical model is revised, and the rotor dynamic model is improved to enhance the computational performance, essential for a real-time simulation. This model is further enhanced in Ref. 15, where a novel gimballed rotor mathematical model is introduced. These models have been implemented and tested using an advanced and professional simulator.

In this paper, we present a novel tilt-rotor flight simulation platform for research and teaching purposes. The main contribution of this work is the design, integration, and implementation of the simulation platform on a portable workstation, while ensuring real-time performance.

Specifically, the simulation platform implements a real-time simulation of the Bell XV-15 aircraft. The mathematical model includes simplified models for the aerodynamics of the whole aircraft, rotors, and engine dynamics defined using the studies of Refs. 14 and 15, where the mathematical model of Refs. 10 and 11 is revised and enhanced. Hence, the simulation is performed in a graphic environment provided by FlightGear to reproduce the simulated flight and to interact with it using command given by the pilot.

The main advantage of the proposed tilt-rotor flight simulation platform is the possibility of executing a flight simulation on a portable workstation to be used by students and researchers without requiring specific and expensive hardware. The proposed tilt-rotor flight simulation platform is also tested with a licensed helicopter pilot returning positive feedback and several suggestions to improve the simulator.

TILT-ROTOR MATHEMATICAL MODEL

The mathematical model used in our tilt-rotor flight simulator platform is mainly based on Refs. 10 and 11, which describe the theory of GTRS, but modified for improved performance, as per our previous works in Refs. 14 and 15. We remark that the validation of the mathematical model is not conducted in this work because it is not the main purpose of this paper. For the study and validation of the mathematical model refer to Refs. 10, 11, 14 and 15.

The mathematical model of the aircraft considers various elements that enable to adequately represent the flight mechanics of the aircraft. The main structure of the tilt-rotor flight simulator is shown in Figure 1, and consisting of several elements that characterize the Flight Control Computer (FCC), the actuation system dynamics, the aircraft dynamics and rigid body Equations of Motion (EoM), as well as the input/output interfaces with the command inputs and the graphic environment. In the following paragraphs, each element of Figure 1 is detailed.

INPUTS

Inputs include the flight commands from the pilot. The pilot interacts with the simulator using USB peripherals, i.e. a flight stick and a pedal board. These commands are then evaluated and normalized to interface with the typical flight controls of the XV-15.

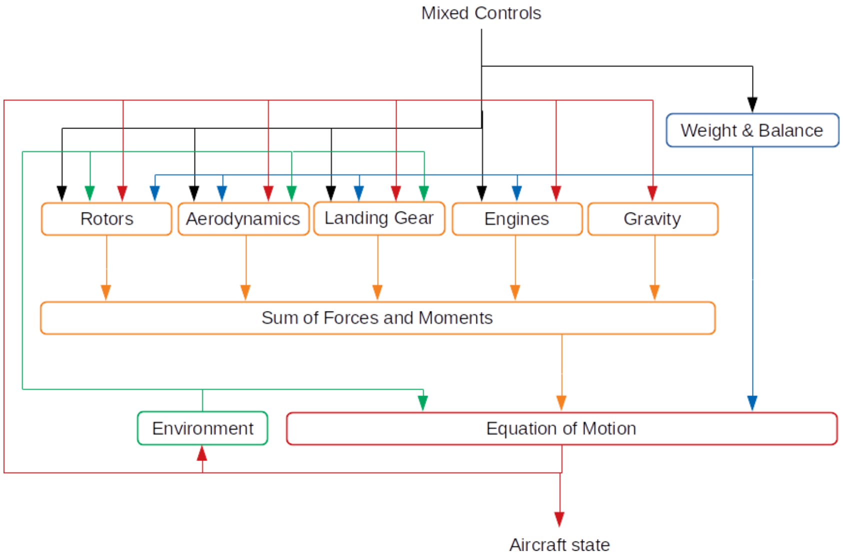


Figure 2: structure of the mathematical model

FLIGHT CONTROL COMPUTER (FCC)

The FCC consists of two main elements: an integrated SCAS and the Collective Governor.

The SCAS (Stability Control and Augmentation System) provides angular rates stabilization and automatic pitch trim capability improving handling qualities in both airplane and helicopter mode.

The Collective Governor is the system that adjusts the collective pitch to maintain a constant number of revolutions depending on the deflection angle of the nacelles.

ACTUATORS

The hydraulic or electric actuators are very complex systems that can introduce several non-linearities in the physics of the aircraft. However, in our simulator actuators are modelled with simple transfer functions avoiding to introduce computational complexity and to guarantee a real-time execution of the flight simulation.

Hydraulic actuators for flight controls represent a system that needs to be properly modelled in an aircraft, because they can induce non-negligible delays both in the pilot control loop and in the stabilization system. For this reason, a first-order transfer function has been implemented to reproduce appropriate delays.

Even though a complete dynamic model of the engine is not implemented, the delay between pilot input (collective and throttle, depending on the flight mode) and engine response is considered. The latter is achieved using a first-order transfer function.

The nacelles actuators have a certain actuation speed that have to be accounted for the correct simulation of the tilt-rotor. In fact, in a tilt-rotor the nacelles command becomes a primary command to move longitudinally and, therefore, a delay in its actuation is critical. In our simulator, it is modelled with a constant actuation speed.

The swashplate allows to translate the pilot's inputs into cyclic or collective blade variations by means of a mechanic present on the rotor. Their implementation is provided in the helicopter flight mode and is essential for maintaining position in hover. This implementation is also modelled with a first-order transfer function.

PHYSICS

The physical model of the aircraft evaluates force and momentum contributions to be integrated into the equations of motion.

Figure 2 illustrates the main contributions evaluated in our tilt-rotor simulator, where the mixed control inputs contain all the tilt-rotor flight control input values, namely rotor collective and cyclic pitch inputs, flaps, aileron, rudder and elevator deflections, and nacelle tilting angle.

Gravity is simply evaluated as a constant force that depends on the weight and rotated according to the Euler angles of the aircraft.

Engines produce a thrust contribution provided by the tilt-rotor engines and due to the exhaust outflow.

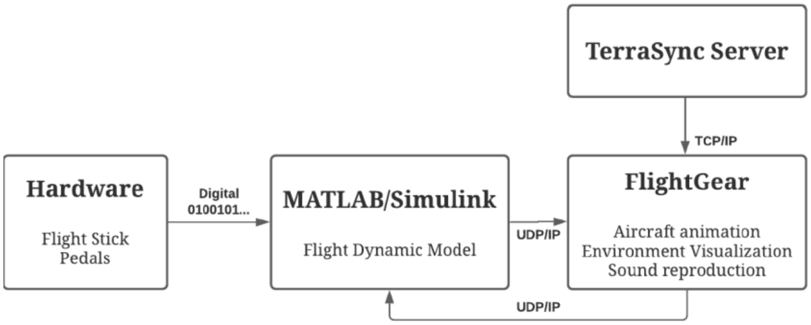


Figure 3: the software architecture adopted in the proposed tilt-rotor flight simulation platform

Rotors produce a variable force and moment for maintaining position and attitude in helicopter mode. Their contribution depends on the conditions of the swashplate, on the aircraft motion and on the environment. The mathematical model implements a multi-blade formulation of the rotor's airloads, and a second order flapping dynamics in which gimbal attitudes and each blade's elastic flapping motion are modelled. The latter is combined with a Pitt-Peters first-order dynamic formulation of the rotor inflow, and a modelling of the wake-induced velocity fields affecting each of the relevant aerodynamic surfaces of the aircraft (wing, vertical stabilizer, and horizontal stabilizer). The overall mathematical formulation accounts for the rotor tilting and allows the dynamic nacelle conversion during piloted simulation. More details about the rotors mathematical modelling are described in Refs. 14 and 15.

Aerodynamics includes mathematical modelling of the aerodynamic forces generated by the following main elements of the tilt-rotor aircraft: fuselage, wing-pylon, horizontal stabilizer, vertical stabilizer. The mathematical model follows nomenclature and layout described in Ref. 11. However, the aerodynamics model has been extensively reviewed and several modifications are introduced compared to Ref. 11. For more details about the aerodynamics refer to Refs. 14 and 15.

Landing gear model evaluates the aerodynamic drag generated during motion, as well as the interaction with the ground: the model considers the damping effect due to the relative compression (with energy dissipation) of the landing gear stem, and friction produced with the ground. Moreover, the longitudinal resistance force on the ground varies with the pressure of the brakes. In our simulator the landing gear is implemented using a proprietary library developed at the ZHAW university ad-hoc modified according to the geometrical properties of the XV-15 aircraft.

The environment block provides a basic atmosphere model for air density, pressure, and temperature. The model is implemented according to the ISA atmosphere. In addition, the environment block allows the user to introduce wind and gusts components into the environment.

As shown in Figure 2, the model also includes a weight and balance block. The latter computes the position of the aircraft center of gravity according to flight condition and nacelles tilt angle: during conversion from helicopter mode to aircraft mode, the nacelles rotation causes the aircraft center of gravity position to shift along the station line of the aircraft. The center of gravity shift along the longitudinal axes of the aircraft can be obtained by simple trigonometric formulations, according to the data provided in Ref. 11.

EQUATIONS OF MOTION (EOM)

The EoM block computes the rigid body dynamics and provides the aircraft position, attitudes, speed, angular and linear accelerations. In the tilt-rotor simulator, the Euler-angles-based formulation provided in Ref. 11 has been replaced with the quaternion formulation of Ref. 16.

DATA EXCHANGE

The output of the tilt-rotor mathematical model consists of all forces and moments generated inside the model, landing gear position, aircraft attitudes, rates and accelerations, as well as the aircraft position in space. Then, the output data is sent to the graphics environment. More details about the graphics environment and the communication protocol adopted are explained in the following section.

SIMULATION ARCHITECTURE

The main contribution of this work is the implementation of the mathematical model and the interaction with the flight control hardware used by the pilot and the graphics environment, while ensuring real-time performance. The main architecture adopted for the proposed tilt-rotor flight simulation platform is shown in Figure 3.

The tilt-rotor mathematical model has been implemented using MATLAB/Simulink®. The use of MATLAB/Simulink® allows the development of a model easy to read and understand, suitable for research and teaching purposes. Moreover, Simulink provides means for developing modular projects, allowing for easy replacement of model sub-parts,

Figure 4: screens captured from FlightGear simulator. Top panel, the aircraft in the simulated environment visualized with the external view. Bottom panel, the Primary Flight Display implemented to interact with the pilot.

and enabling the use of the tilt-rotor simulator for testing and validation purposes.

FLIGHTGEAR

The graphics environment is provided by FlightGear (Ref. 17), an open-source and cross-platform flight simulator developed for research, academic and industrial purposes. FlighGear provides a realistic three-dimensional simulation environment including terrain, airports, cities, vegetation, all over the globe. By default, it provides a flight simulation platform with several aircraft ready to use.

However, this simulator has been adjusted to reproduce the aircraft status provided by MATLAB/Simulink® in a three-dimensional environment. Practically, the developed MATLAB/Simulink® model evaluates the status of the aircraft, including position and attitude, as well as the rotational speed of the rotors, the position of the moving surfaces and the status of the landing gears, which are sent to the FlightGear environment that reproduces an animated three-dimensional model of the aircraft, as well as reporting flight data to the virtual cockpit on FlightGear.

The communication between MATLAB/Simulink® and FlightGear is performed using an UDP communication protocol. UDP is a lightweight communication protocol suitable with time-sensitive applications.

To display a realistic aircraft with appropriate animations and sounds, an aircraft already available on the FlightGear database has been chosen. Specifically, the Boeing V-22 Osprey is selected because of several similarities with the XV-15. Several modifications have been applied to this model to disable the default flight mechanics provided by the open-source physical simulator JSBSim and enable the interaction with the mathematical model provided by MATLAB/Simulink®.

In order to show the aircraft status to the pilot, a Primary Flight Display (PFD) has been added to the aircraft graphical model including several instruments, such as the artificial horizon, the compass, the altimeter, the vertical speed indicator, the CAS speed indicator, the RPM gauge, the nacelle position gauge, the flaps position indicator, and the gear position indicator.

To improve the pilot experience, FlightGear simulator reproduces a simplified view of a portion of planet Earth on which the aircraft is located, including aerial infrastructures, but also vegetation and several obstacles. This feature is provided by TerraSync, a tool of FlightGear that allows to continuously update the flight scenario during the simulation based on the position of the aircraft.

As result, FlightGear reproduces and aircraft very similar to the XV-15 with the same flight controls and dynamics in a

Figure 5: the hardware adopted in the tilt-rotor flight simulation platform. Top panel, the flight stick. Bottom panel, the rudder pedal.

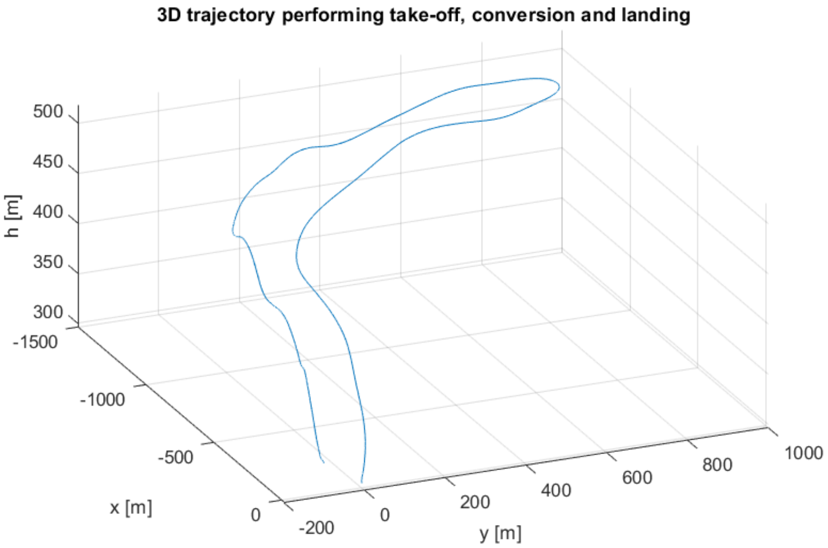


Figure 6: the trajectory performed using the tilt-rotor flight simulation platform. The XV-15 aircraft performs a take-off in helicopter mode, followed by a conversion and, after a turn on left, a landing close to the starting position

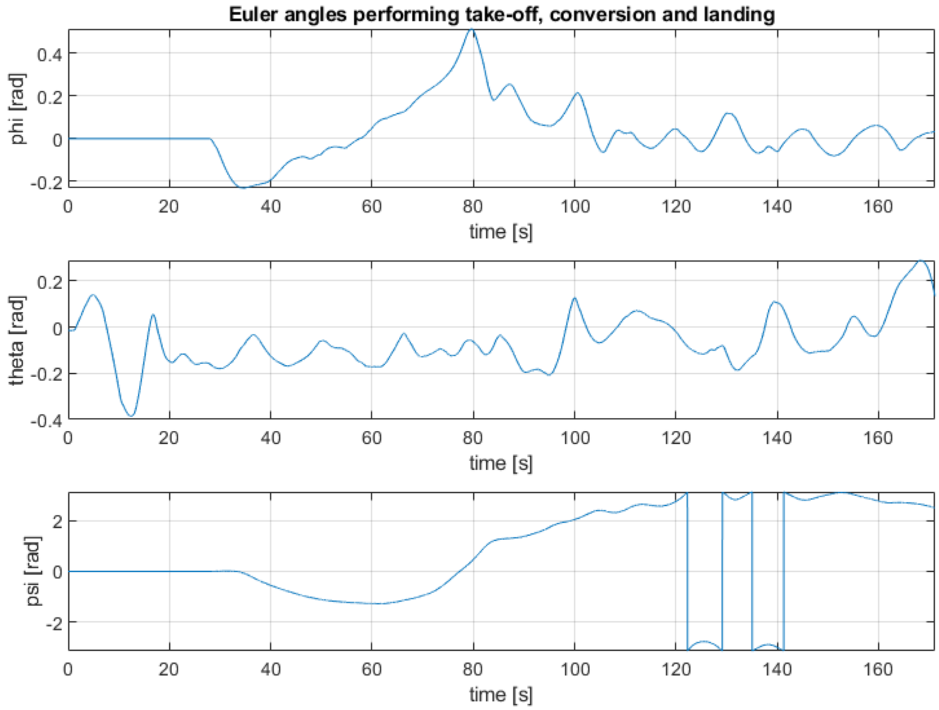


Figure 7: Euler angles of the XV-15 aircraft performing the trajectory of Figure 6

realistic simulation environment. Figure 4 shows the aircraft simulated in FlightGear.

FLIGHT CONTROL HARDWARE

The hardware used to provide the flight commands by the pilot consists in two commercial USB peripherals: a flight stick and a rudder pedal.

The flight stick is set as shown in Figure 5 to control the lateral and longitudinal axis, flaps, position of the nacelles, the parking brake, and others essential controls. At the bottom is locate the collective lever, which allows to set the pitch of the blades, because the throttle is automatically managed by the governor that sets the speed of the engine based on the position of nacelles.

Instead, the rudder pedal is used to provide a precise control of the yaw command, which consists of a rudder command or a differential cyclic command for the two rotors in helicopter mode. Moreover, pedals can be pressed to generate a brake command on the landing gear. The rudder pedal is shown in Figure 5.

REAL-TIME SIMULATION

An important feature of our tilt-rotor flight simulation platform is the real-time performance. Guarantee real-time

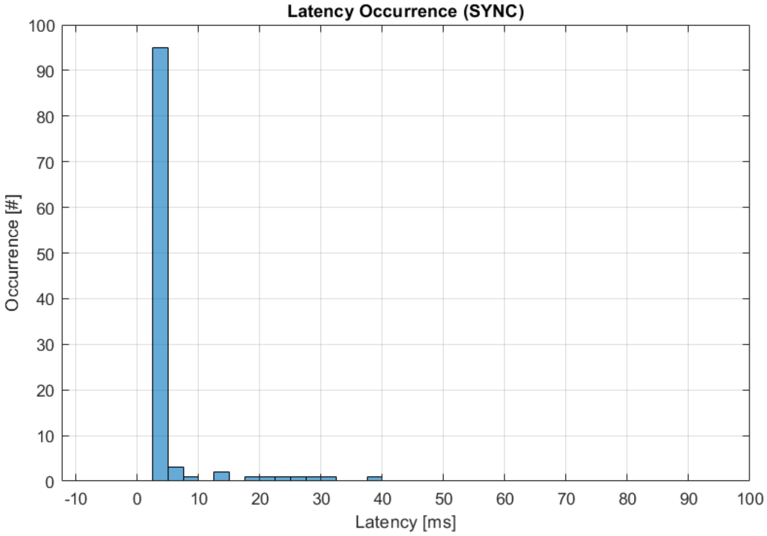


Figure 8: latency occurred during the flight simulation of Figure 6

performance is a challenge because it is necessary to synchronize the physical simulation time with the processor clock while ensuring a simulation with a realistic speed and low latency for the correct interpretation of the flight dynamics by the pilot. In fact, as defined by the CS-FSTD(A) standard "*(Latency) the visual system, flight deck instruments and initial motion system response shall respond to abrupt pitch, roll and yaw inputs from the pilot's position within 150 ms of the time, but not before the time, when the airplane would respond under the same conditions.*"

In our tilt-rotor simulator we have exploited the Simulink® Desktop Real-Time™ (SLDRT), a tool that provides a real-time kernel for executing Simulink® models including library blocks that connect I/O devices to generate simulations with hardware inputs.

Using Simulink® Desktop Real-Time™ library, great effort was required (including software optimizations to speed-up the simulation) to provide the correct synchronization of processor clock and physical simulation, and ensure real-time performance of the model. Moreover, particular focus was put into the synchronization of the communication from/to FlightGear using a UDP communication protocol to guarantee the real-time performance.

RESULTS

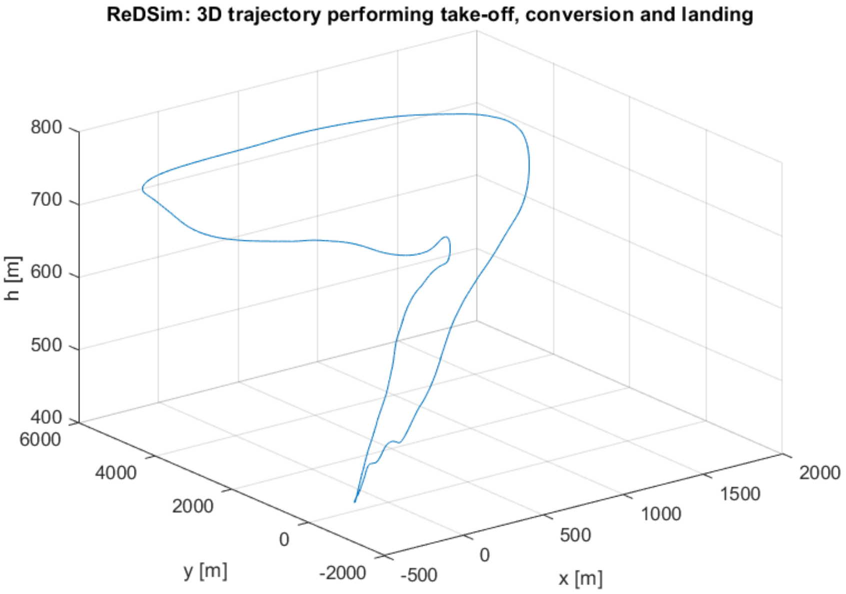
As discussed in the previous Sections, the tilt-rotor flight simulation platform is mainly implemented using MATLAB/Simulink® and FlightGear. All the developed software is implemented and tested on a commercial pc (Dell® Precision 7550).

Figure 4 shows two screens of the simulation in FlightGear: on the left the aircraft in the simulated environment, and, on the right, the PFD of the virtual cockpit. As described in the previous sections, in these results, the displayed aircraft is the Boeing V-22 Osprey, only used for visualization in FlightGear. In fact, the mathematical model exploited by the simulator is provided by the MATLAB/Simulink® framework considering the Bell XV-15 dynamics. Instead, the PFD is essential for the pilot to be aware of the flight condition and to check the flight status. The result is an aircraft very similar to the Bell XV-15 with the same flight controls and dynamics.

In order to validate the quality of the simulation and demonstrate the real-time capability of the developed simulator, several tests have been performed: one of the tests (Figures 6 and 7) consisted of a vertical take-off followed by a conversion to airplane mode by progressively turning the nacelles forward; at the end of conversion, the aircraft turns left returning close to the initial position to land in helicopter mode. This flight simulation task is performed by a pilot using the control stick and the pedal board.

The main purpose of these tests is to evaluate the real-time performances. Latencies occurred during the whole simulation are evaluated focusing on the latency introduced by the interaction with FlightGear and the latency introduced by tilt-rotor mathematical model implemented in Simulink®. As a result, in the test of Figure 6 the overall latency introduced by the exchange of data with FlightGear by the tilt-rotor model EoM have been evaluated. Figure 8 shows the occurrence of delay during the simulation performed in Figure 6. In most of the simulation the delay is between 2.5 ms and 5 ms, except in some time step at the beginning of the simulation where the delay reaches 40 ms. This behavior at the beginning of the simulation is mainly due to FlightGear that loads the simulation scenario through the TerraSync utility. This process requires several resources at the expense of the resources required by the tilt-rotor model implemented in Simulink®.

Figure 9: the trajectory simulated using the ReDSim simulator. The XV-15 aircraft performs a take-off in helicopter mode, followed by a conversion and, after a turn on left, a landing close to the starting position



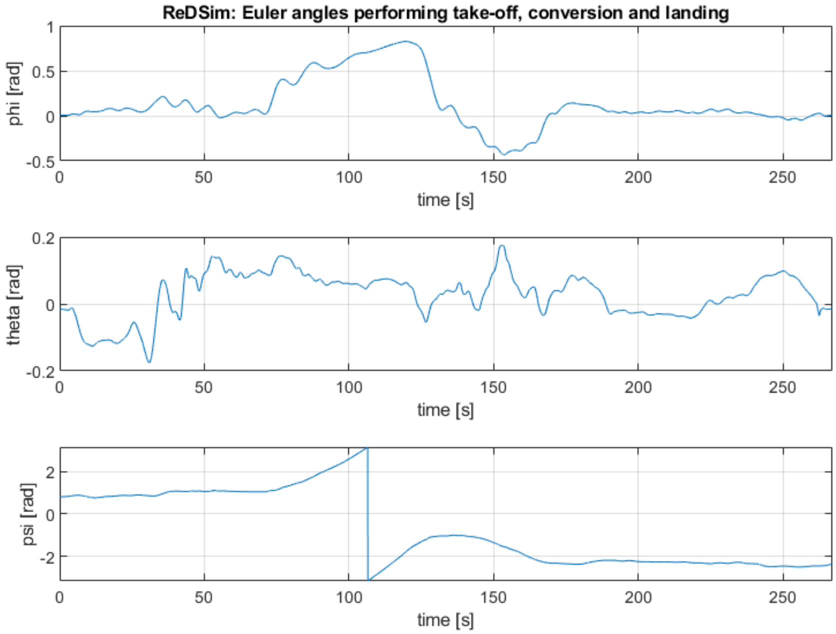


Figure 10: Euler angles of the XV-15 aircraft performing the trajectory of Figure 9

Summarizing, the overall latency is definitely an acceptable value to guarantee real-time performance with an update frequency of 50/60 Hz even using a commercial portable pc.

The simulated flight of Figure 6 is performed by a licensed helicopter pilot. After a training phase necessary to familiarize himself with the presented tilt-rotor simulation platform and the controls, the pilot easily controlled the simulated XV-15 aircraft. For comparison, the same pilot has conducted a similar flight in the Research and Didactics Simulator (ReDSim). ReDSim is a multi-purpose real-time flight simulation platform installed and implemented in the ZHAW university for research, teaching, and development activities. The resulting trajectory performed in the ReDSim is shown in Figures 9 and 10.

After these tests, we have asked the pilot for a feedback about the flight experience with our tilt-rotor flight simulation platform, even in comparison with the ReDSim. While providing very positive feedback regarding the piloting experience and realistic simulation environment and realistic response times, some limitations were highlighted.

The first concerns the field of view of the simulator. Especially in the helicopter mode, the pilot observes the surrounding environment to maintain a stable attitude of the aircraft. The display of the laptop does not allow a wide field of view making it more difficult to control the aircraft in helicopter mode in the take-off and landing phases. This limitation is highlighted in the flight of Figure 6, where the pilot made a pure vertical take-off and landing due to the difficulty of controlling the aircraft in this mode. On the contrary with ReDSim, the pilot takes off while moving on the longitudinal direction by acting on the aircraft pitch. For this reason, the pilot stated that the control of the aircraft is easier with the external camera in FlightGear, since it has a wider field of view.

Another limitation is due to the use of the selected flight control hardware (flight stick and pedal) which has a different dynamic from the real one, especially for the collective lever. However, the use of commercial and low-cost hardware is one of the key elements to make our tilt-rotor simulator portable and low cost.

CONCLUSIONS

In this paper we have presented a tilt-rotor flight simulation platform for research and teaching purposes. The tilt-rotor simulator is implemented using MATLAB/Simulink® and FlightGear, controlled by a pilot using commercial hardware. The result is a portable tilt-rotor flight simulation platform runnable on a commercial laptop, while ensuring real-time performance.

The developed tilt rotor flight simulation platform presents more than satisfactory results providing a real-time simulation of an aircraft very similar to the Bell XV-15 with the same flight controls and dynamics. Simulations with a licensed helicopter pilot demonstrate that the proposed tilt-rotor simulator offers a good flight experience.

Compared with the ReDSim simulator installed at the ZHAW university, our simulator has some limitations, but mainly due to the low-cost hardware used, such as the display with a limited field of view and the non-realistic flight control hardware.

The main benefit of the proposed tilt-rotor simulator is the ability to run the flight simulation on a portable and commercial pc, to be used by students and researchers without requiring specific and expensive hardware.

Future works will include the development of graphic elements, such as a three-dimensional model of the Bell XV-15 aircraft to be included in FlightGear, as well as the development of a realistic instrumentation that reproduces the one on-board the Bell XV-15. Moreover, the integration of the hardware including a lever collective, and a realistic stick control will better represent the Bell XV-15 aircraft.

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ACKNOWLEDGMENTS

This activity is part of a Doctoral Research Program (Ph.D. in Aerospace Engineering at Politecnico di Torino) and M.Sc. in Aerospace Engineering at Politecnico di Torino (Mr. Federico Veronese) supported by Zurich University of Applied Sciences, Centre for Aviation.

REFERENCES

1. Padfield, G. D. (2018). Helicopter flight dynamics: including a treatment of tiltrotor aircraft. John Wiley & Sons.
2. Derrouaoui, S. H., Bouzid, Y., Guiatni, M., & Dib, I. (2022). A comprehensive review on reconfigurable drones: Classification, characteristics, design and control technologies. Unmanned Systems, 10(01), 3-29.
3. Maisel, M. D. (2000). The history of the XV-15 tilt rotor research aircraft: from concept to flight. National Aeronautics and Space Administration, Office of Policy and Plans, NASA History Division.
4. Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., & Antcliff, K. R. (2018). VTOL urban air mobility concept vehicles for technology development. In 2018 Aviation Technology, Integration, and Operations Conference, 38-47.
5. H. Rosenstein (1992). Short course on tilt-rotor aerodynamics. Short Course on Helicopter and V/STOL Technology, Penn State.
6. Dreier, M. E. (2007). Introduction to helicopter and tiltrotor flight simulation. American Institute of Aeronautics and Astronautics.
7. Allerton, D. (2009). Principles of flight simulation. John Wiley & Sons.
8. Dugan, D. C., Erhart, R. G., & Schroers, L. G. (1980). The XV-15 tilt rotor research aircraft. NASA.
9. Churchill, G. B., & Dugan, D. C. (1982). Simulation of the XV-15 tilt rotor research aircraft. NASA.
10. Harendra, P. B., Joglekar, M. J., Gaffey, T. M. & Marr, R. L. (1973). V/STOL tilt rotor study. A mathematical model for real time flight simulation of the Bell model 301 tilt rotor research aircraft. NASA.
11. Ferguson, S.W. (1988). A Mathematical Model for Real-Time Flight Simulation of a Generic Tilt-Rotor Aircraft. NASA.
12. Kleinhesselink, K. M. (2007). Stability and control

modeling of tiltrotor aircraft. Master's thesis. University of Maryland, College Park.

13. McVicar, J. S. G. (1993). A generic tilt-rotor simulation model with parallel implementation. Ph.D. thesis. University of Glasgow.
14. Barra, F., Capone, P., Monstein, R., Godio, S., & Guglieri, G. (2019). Implementation of a comprehensive mathematical model for tilt-rotor real-time flight simulation. In 45th European Rotorcraft Forum, Warsaw, Poland.
15. Abà, A., Barra, F., Capone, P., & Guglieri, G. (2020). Mathematical modelling of gimballed tilt-rotors for real-time flight simulation. Aerospace, 7(9), 124.
16. Stevens, B. L., Lewis, F. L., & Johnson, E. N. (2015). Aircraft control and simulation: dynamics, controls design, and autonomous systems. John Wiley & Sons.
17. FlightGear developers and contributors. (2021). FlightGear. Retrieved from https://www.flightgear.org/.