University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

MODEFLIER

Mode-Demonstrating Flying Laboratory: Instruction and Experiment in Real-time

Approvals

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1.0 Problem or Need

The flight dynamics of conventional aircraft are complex and involve highly coupled, nonlinear equations of motion. These equations describe many of the intricacies of flight, and from eigen-analysis are obtained the common natural modes of conventional aircraft, namely the phugoid, Dutch roll, spiral, short period, and roll modes. The complexity of these equations makes them difficult to conceptualize, and their physical implications on the motion of the aircraft are not intuitive. Moreover, the natural flight modes of an aircraft can be difficult to observe, either because they are brief, subtle, or both. In the undergraduate curriculum for Aerospace Engineering Sciences (ASEN) at the University of Colorado at Boulder (CU), the dynamics of flight are introduced in a junior level course: ASEN 3128: Aircraft Dynamics. It currently uses software simulations as a teaching tool for students being exposed to the material for the first time. The software used provides insight to the dynamics of an aircraft; however, an image on a screen is not always the best demonstration of an aircraft's motion, and abstract concepts have the potential to be misunderstood without a physical model of these modes.

The Mode-Demonstrating Flying Laboratory: Instruction and Experiment in Real-time (MODEFLIER) shall be a small, low-cost, flying laboratory system that demonstrates the phugoid, Dutch roll, and spiral modes for an aircraft for the ASEN 3128 course. It will be controlled by a remote ground station, which will also display real-time flight data specified by the aircraft state array[*] to resolutions of 1° for Euler angles, 1 m for position, and 0.5 m/s for air velocities. It will allow for the ground controller to switch the phugoid mode, the Dutch roll mode, or the spiral mode "on" and "off" during flight. The ground controller will also have the capability to input a gain on a desired control surface of the aircraft via remote control to show how various perturbations in control surfaces affect these flight modes. The natural mode behavior of the aircraft shall be noticeable when observed by groups of students, up to 10 at a time, who at the same time will be watching a data stream of the aircraft state array at the ground station. By visual observations from the ground, students will be able to estimate Euler angle perturbations within 5° while each angle is within 20° of trim. The aircraft will record and store video on-board to provide an onboard perspective of the various flight modes. The entire system (test article and ground station equipment) will be compact, so as to fit in a conventional SUV for easy transportation.

The ultimate goal of this project is to benefit future students of the ASEN 3128 course by providing them with a physical system in a course that is highly dependent on a physical understanding of aircraft motion. It will help students to visually see aircraft motions that are difficult to describe with words and still pictures alone.

2.0 Previous Work

The natural modes for the dynamics of a conventional aircraft are well known. The longitudinal modes include the phugoid and short-period modes, while the lateral modes include the spiral, roll, and Dutch roll modes. These modes arise from a linearization of the equations of motion for an aircraft. As such, these modes represent a theoretical approximation of the behavior of an actual aircraft near a trim state[1]. For educational purposes, various methods have been employed to visually display these theoretical modes in physical system.

One approach is to use a wind tunnel to simulate aircraft dynamics. This method was utilized by Merrill[2]; he constructed an aircraft that was inserted into a wind tunnel with a gimbal mount that allowed for three degrees of freedom: roll, pitch, and yaw. Merrill found that the longitudinal test data agreed with the theoretical results which confirmed the usefulness of a wind tunnel; however, Merrill encountered difficulties in replicating the lateral motion of an aircraft. In addition, the friction of the gimbal caused the model to not replicate flight conditions perfectly[2].

Another approach used by the University of Southampton[3] was the use of a passenger Jetstream flying laboratory with which students experience a one-week flight-testing course. The students experience the natural modes of the aircraft in flight[3]. While this method provides an excellent learning experience, the purchase of a passenger aircraft is quite expensive.

Computer flight simulators have also been adopted to demonstrate the natural modes of an aircraft. These simulators often only provide visuals of how the aircraft behaves yet lack educational content. Simulations can be a cheaper alternative to actual flight, but might not be the best way to understand the behavior of an aircraft[4]. Similarly, in CU's ASEN 3128 course the students have been exposed to the natural modes of a conventional aircraft through a software package capable of providing graphical results. Unfortunately, no representation of a physical aircraft was provided, which hampered the understanding process.

This project appears to be the first attempt at using a small, unmanned aircraft to demonstrate the natural modes of an aircraft in an educational setting. The use of an unmanned aircraft capable of flight allows for greater freedom of translational motion than a wind-tunnel model, while requiring significantly fewer expenses than a passenger aircraft. The flight

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[*] The aircraft state array includes twelve elements: x, y, and z positions; u, v, and w velocities; ϕ, θ, and ψ Euler angles; and p, q, and r angular rates.

characteristics of the aircraft will allow the natural modes of the aircraft to be visible and distinguishable to an observer on the ground, allowing for the physical system to visually demonstrate the theoretical dynamical modes of the aircraft.

3.0 Specific Objectives

In order to meet the customer's requirements for success, the MODEFLIER aircraft shall be capable of safe and reliable take off, steady flight, and landing without modifying the environment. This aircraft will display three natural aircraft dynamical modes: the phugoid mode, spiral mode, and the Dutch roll mode; the aircraft will then return to steady flight. An onboard autopilot will command the aircraft, but the aircraft will also receive input from a ground station. An operator at this ground station will be able to switch on and off the exhibition of the dynamic modes, and a pilot will have the option to directly pilot the aircraft via remote control (RC).

The aircraft will also download flight data to the ground station for storage and visual display of the data. These flight data will include roll, pitch, yaw, and flight angles, altitude and horizontal positions, and airspeed. A video camera mounted on the aircraft will provide additional visual information on the flight of the aircraft, and this video will be available for download after the aircraft lands.

To validate the product design and verify its performance, the aircraft and ground station will be put through a testing gauntlet. All of the subsystems, both manufactured and store-bought, will be tested for functionality and performance prior to the first flight test. These ground tests will include testing of the communications system, data recording system, propulsion system, and others. Airframe tests will ensure that the airframe is structurally stable and possesses the physical characteristics used in simulations of the modal responses.

Following successful ground testing, the aircraft will go through flight testing. This will include takeoff and landing, steady autonomous flight, mode demonstration, and manual RC override of the autopilot by the pilot. The team will evaluate the performance of the aircraft by comparing the recorded data to computer simulations. To validate that the modes have been successfully demonstrated, the flight data will be compared to flight parameters derived from the customer's specifications of visible modal performance.

3.1 Success Levels

- Level 1 – The aircraft shall demonstrate two of the three modes in flight (based on later trade studies) one time each so that an observer with 20/30 vision will be able to identify the roll, pitch, and yaw angles of the aircraft to within 5° when each angle is within 20° of its trim value for level flight at both the operational altitude and a slant angle above 30°. The phugoid mode will display several periods (exact number of oscillations TBD), each with pitch angle amplitude greater than approximately 5° (exact amplitude TBD). The Dutch roll mode will display several periods (exact number of oscillations TBD), each with roll angle amplitude greater than approximately 5° (exact amplitude TBD). The spiral mode will display several 360° yaw angle turns (exact number of turns TBD), or until an unrecoverable roll angle (the magnitude of which will be determined by the airframe dynamics) is reached. It shall be controlled remotely and the modes will be initiated by the pilot with a sudden change of the control surfaces. The aircraft will store the flight data on board, as well as record and store flight video, and both will be accessible after landing. The aircraft shall be replicable for a cost below $1,000 and the ground station shall be replicable for a cost below $2,000. Both the ground station and airplane shall fit in the back of a standard SUV with approximately a 150x100x90 cm cargo space. Additionally, the aircraft will be capable of takeoff and landing without modification to the test environment.
- Level 2 – All three modes will be demonstrated while meeting visibility requirements, and flight data will be downlinked from the aircraft to the ground station and displayed at a rate of at least 10 Hz. These data will include roll, pitch, yaw, and flight angles at a resolution of 1°; altitude and horizontal position at a resolution of 1 m, and airspeed at a resolution of 0.5 m/s. The ground station shall accommodate up to 10 students to view data, while the aircraft and ground station shall be able to perform 10 demonstrations in 8 hours. Level 1 shall also be met.
- Level 3 – The autopilot shall be capable of maintaining the aircraft in steady flight, initiating the three modes, changing the gains during flight, and shall turn the behavior "on" and "off" at will. The aircraft will fly autonomously, either by tethered flight or with Federal Aviation Administration (FAA) approval in the form of a Certificate of Authorization (COA)[5], and an RC pilot will be present in case of anomaly. Levels 1 and 2 shall also be met.

4.0 Functional Requirements

In the course of this design project, an Unmanned Air System (UAS) will be developed for the ASEN 3128 class for use as a physical laboratory. The three main components of the system are the airframe, the autopilot, and the ground station, all of which will communicate and interface with each other to accomplish the functional requirements.

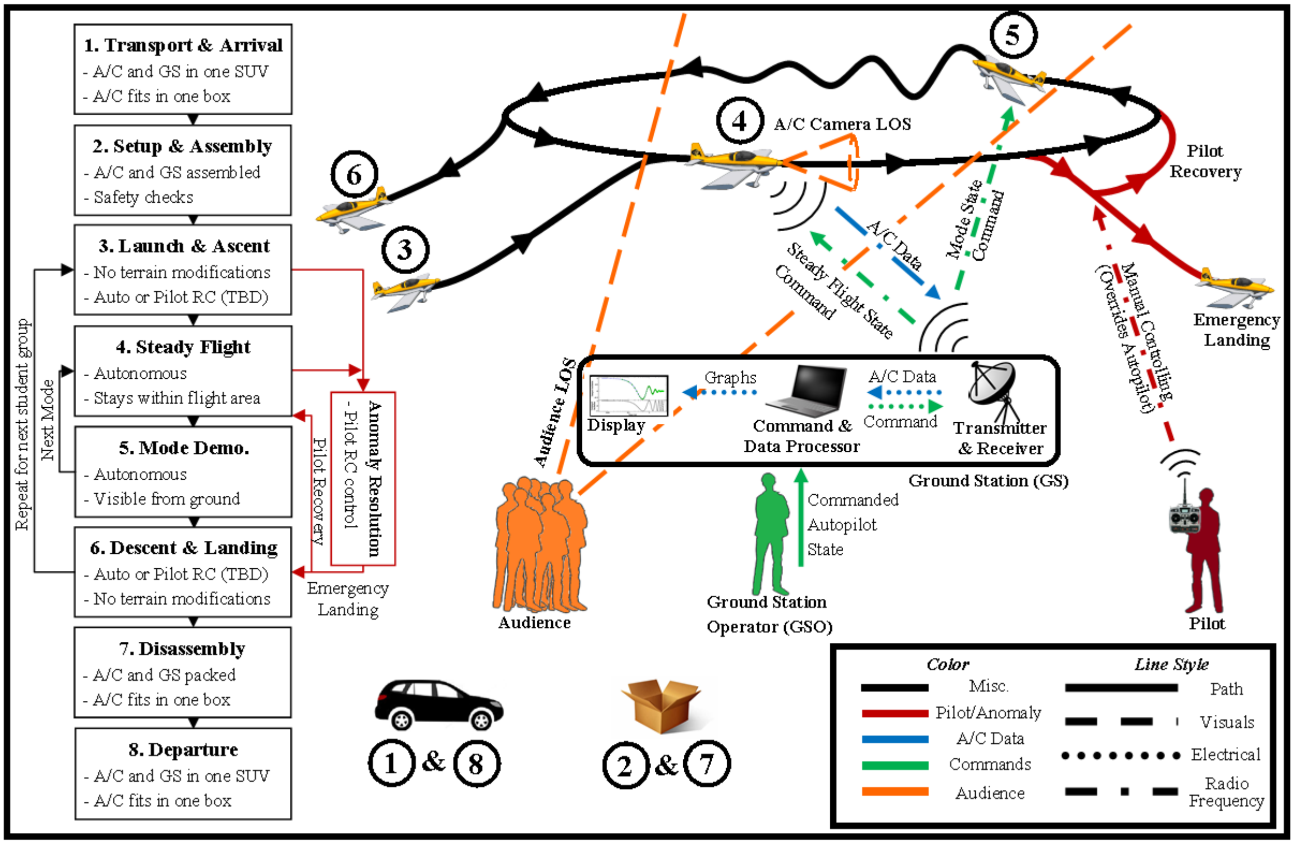

Figure 4.1: Concept of Operations (CONOPS) Diagram.

The CONOPS diagram shown in Figure 4.1 above, details the operation of the MODEFLIER aircraft and its ground station to demonstrate the 3 natural aircraft modes, the phugoid, spiral and Dutch roll mode. Simultaneously, the MODEFLIER system will measure and display real-time data and also record video during flight for later use.

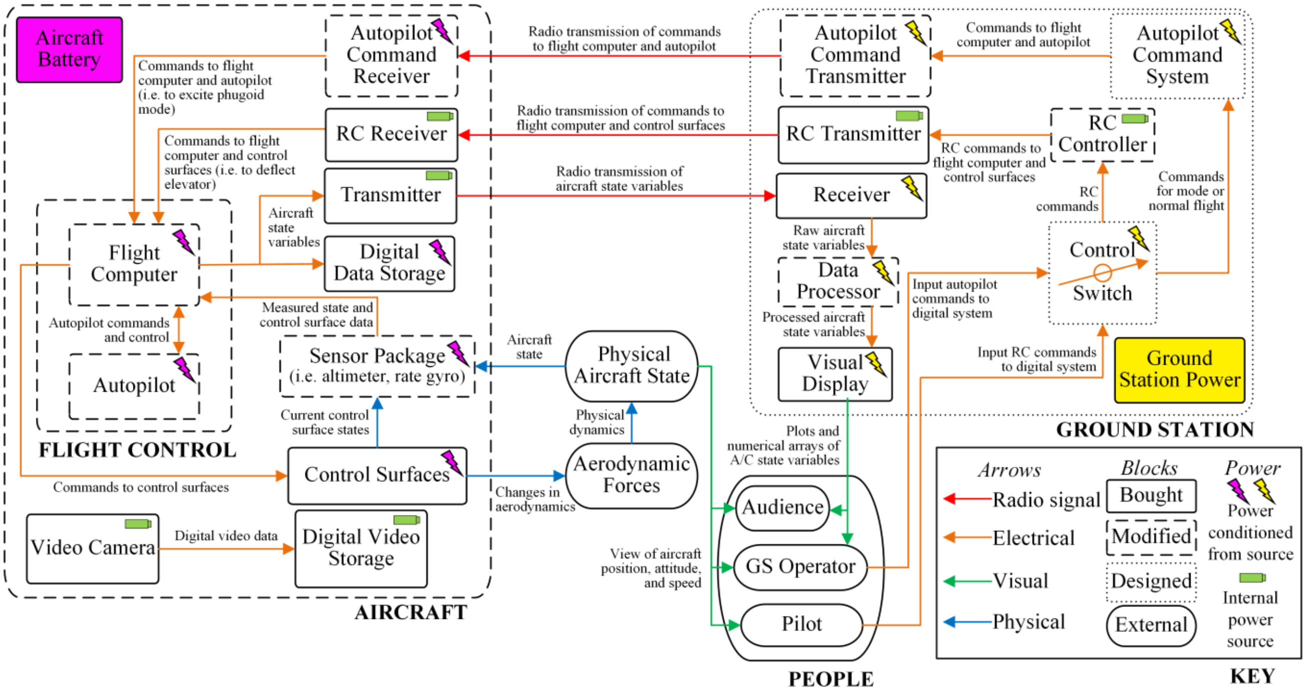

Figure 4.2: Functional Block Diagram (FBD).

The FBD in Figure 4.2 on page 4 outlines the MODEFLIER system and its interaction with the people involved. The diagram displays how the instruments are powered, controlled and how they relate with each other during operation. The MODEFLIER then outputs the physical aircraft state variables and a visual video recording of the MODEFLIER aircraft during flight.

5.0 Critical Project Elements

5.1 Technical Elements

5.1.1 Phugoid, spiral, and Dutch roll mode demonstration

It is vital to the success of this project for the aircraft to be able to exhibit the phugoid, spiral, and Dutch roll modes in a manner that is clearly visible from an audience located on the ground. This requirement constitutes an unusual design driver for the airframe, which goes outside the expertise of the team members, and it entails the expenditure of a significant amount of time and effort. Moreover, it is central to all the other functional requirements and to the goal of the project.

5.1.2 Autopilot design

The aircraft must fly autonomously, and the modes are to be triggered during flight by the autopilot following a direct command from the ground station. Not only is this project element necessary for the complete success of the system, but it also requires a large amount of time and expertise due to its high level of complexity.

5.1.3 Validation of the mode demonstration

The extent to which the phugoid, spiral and Dutch roll modes are successfully demonstrated must be quantified. The validation process for this functional requirement is not trivial, yet it is of great importance as the project's success is dependent on it. Moreover, the approach used is highly influenced by the flight environment available, it is extremely complex to model, and requires the coordination of numerous logistic aspects.

5.1.4 Ground station electronics and communication

The ground station is inherently tied to success of the mission as any lapse in command or data downlink results in mission failure. It is an aspect of the project that carries high risk and is required to be highly reliable. Additionally, there are no team members that carry much communication or electronic experience, making the ground system and communications a unique challenge.

5.2 Logistical Elements

5.2.1 FAA approval

As a flying, unmanned vehicle, the aircraft must meet the criteria for FAA authorization for autonomous outdoor flight. Permission from the FAA in the form of a COA must be obtained not only for various test flights necessary for model validation, but also for future use in ASEN 3128. This process takes time and introduces a large amount of risk and uncertainty into the design strategy to adopt. In addition, no team member has experience with the process.

5.2.2 Location

A suitable flight location for the aircraft must be determined and acquired. Due to FAA restrictions, limited time, and availability of flight locations several feasible options will need to be considered, including both indoor and outdoor locations. The flight location is a critical component that will drive the method adopted for testing and validation of the functional requirements, as well as the aircraft design. In addition, its uncertainty adds a considerable amount of risk and complexity in modeling the flight environment.

5.3 Financial Elements

There are financial constraints on the reproducible costs of the airframe and the ground station—$1,000 and $2,000, respectively—but at this time these constraints are not considered to be critical.

6.0 Team Skills and Interests

Table 6.1 presents the areas of expertise and interests of the team members related to the critical project elements defined in Section 5.0.

Table 6.1: Team skills and interests.

Critical Project Elements	Team members and associated skills/interest
Phugoid, spiral, and Dutch roll mode demonstration	All team members—Firm understanding of aircraft dynamics theory and what contributes to each mode Christian Ortiz Torres – Interest in aircraft control systems, aerodynamics, and testing Matthew Slavik – Experience in RC aircraft design, manufacturing, and testing; interest in systems engineering structures and CAD Hindrik Wolda – Interest in aircraft Control Law design and aerodynamics Riccardo Balin– CFD and CAD experience; interest in aerodynamics, manufacturing, and control systems Jas Min Ng – Interest in design and manufacturing Jeffrey Snively – Machine shop experience; interest in design and manufacturing Tyler Smith – Interest in fluids, CAD, and machining
Autopilot design	David Thomas—Experience with C programming; interest in developing an aircraft autopilot Tyler Smith – Experience with C and assembly language experience Hindrik Wolda – Control system modelling experience; interest in aircraft control laws, aircraft design and performance
Validation of mode demonstration	Hindrik Wolda – Experience with aircraft flight testing procedures Christian Ortiz Torres – Interest in safety and flight testing
Ground station electronics and communications	Tyler Smith – Interest in avionics and flight communication Quinn Kostelecky – Experience with software, analog and digital circuits; interest in communications
FAA approval	Hindrik Wolda – Experience with industry dealings with the FAA
Location	All team members – Determined to mediate with CU Athletics or other institutions to obtain a flight location

7.0 Resources

Table 7.1 presents the resources available to the team that go outside the expertise and knowledge of the members, again related to the critical project elements described in Section 5.0.

Table 7.1: Team external resources.

Critical Project Elements	Resources
Phugoid, spiral, and Dutch roll mode demonstration	ASEN 3128 course textbooks Expertise of CU professors
Autopilot design	Expertise of CU professors and ITLL staff
Validation of mode demonstration	Code developed in ASEN 3128 for mode demonstration
Ground station electronics and communications	Expertise of CU professors
FAA approval	Experience of James Mack FAA required for approval of COA
Location	CU Athletics – Balch fieldhouse, the bubble, Coors event center Arvada Associated Modelers Airfield

8.0 References

[1] Etkin, B., and Reid, L. D., *Dynamics of Flight: Stability and Control*, 3rd ed., John Wiley & Sons, Inc., Hoboken, NJ, 1996, Chap. 6.

[2] Merrill, J. C., “A Remotely Controlled Wind Tunnel Model for the Demonstration of Aircraft Stability and Control Characteristics,” Master’s Thesis, Naval Postgraduate School, Monterey, CA, June, 1975.

[3] “Launch Your Career: Aeronautics & Astronautics Undergraduate Courses 2015,” University of Southampton, URL: http://www.southampton.ac.uk/engineering/ undergraduate/prospectus/aero_astro.page? [cited 3 Sept. 2014].

[4] Frew, E., “ASEN 3128 Aircraft Dynamics: Spring 2014 Syllabus,” University of Colorado at Boulder, Jan., 2014.

[5] “FAA COA,” *RECUV Operations*, RECUV, University of Colorado at Boulder, URL: https://recuv-ops.colorado.edu/projects/faa_coa/wiki [cited 13 Sept. 2014].