A Full-Flight Simulator of the 1903 Wright Flyer

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Abstract

In recognition of the centennial of powered flight, a project has been launched to build a simulation replica of the Wright 1903 Flyer and demonstrate to a wider public the achievements of the Wright brothers. This paper describes the simulation and modelling of the flight control system and flight dynamics of the 1903 Flyer, and the incorporation of these properties into a specially-built "virtual replica" of the same airplane.

From analysis of simulations this aircraft has been shown to possess significant instabilities in its lateral directional axes, and severe instabilities in the longitudinal axis. Meanwhile, control over the dynamics was limited by the effectiveness of the input devices: The canard's pitch angle was controlled by a flexible chain-driven mechanism, and the lateral controls (with inter-connected wing warping and rudder) were actuated through a hip cradle.

The simulation of this airplane remains a major challenge due to two main aspects: The availability of accurate data is limited, and the dynamics of the vehicle necessitate good motion cueing. These aspects will be discussed in detail in the paper.

The paper concludes with a description of the design requirements for the full-flight simulator. With the aim of demonstrating the stability and control challenges, the simulator incorporates the same control environment as the original airplane, and provides motion, visual and control force feedback to the candidate pilot.

Introduction

In addition to being recognized as the pioneers of aviation for achieving the first powered and controlled heavier-than-air flight Wilbur and Orville Wright's most significant contribution, one that is often not fully recognized – the *control* over that vehicle during its sustained flight. Manually controlling the 1903 Wright Flyer was in itself was an exceptionally difficult task due to its unstable flight characteristics. The Wrights also had no prior formal training in powered flight but relied on their innate capacity to sense the vehicle motions, to visualize its flight path, and to adjust the control inputs to maintain a stable pilot-vehicle system. Orville and Wilbur quickly discovered that the 1903 Flyer required very careful manipulation of the "forward rudder" (as their canard was then referred to) to maintain flight. This coupled with the turbulent wind conditions present at Kill Devil Hill that day made the task indeed a very challenging one.

Since the first flights of the Wrights on 17 December 1903, both aerospace and simulation technologies have progressed hand-in-hand. Today, the aerospace community continues to demonstrate an interest in the challenges that faced the Wrights (and all aviation pioneers) in understanding and applying the rudimentary knowledge of aerodynamics and stability and control that was then state-of-the-art [1, 2, 3].

The goal of this project was to design a high- fidelity simulator of the 1903 Wright Flyer, which could serve as a training tool, and educational facility and a technology demonstrator. Particular attention was lent to the reproduction of the dynamic characteristics and the reproduction of the physical cues. The resulting design is a virtual replica of the 1903 Flyer, able to reproduce a pilot-vehicle interface similar to the original airplane. In addition to the objective of developing a high-fidelity simulation of the Wright Flyer, we expected a wider interest in the opportunity to fly the virtual Wright Flyer. To make that possible for pilots and non-pilots having a range of flying experience, a flight control system was developed to ease the control of this particular aircraft.

In 2002, a paper was written on the optimization of the motion cueing algorithms and motion-base mechanism pertaining to the 1903 Wright Flyer [4]. The results of this paper showed that the stabilization of the vehicle dynamics in the simulation environment remains a challenge. It was also the intention of the authors and others to realize an operational simulation of the 1903 Wright Flyer. What has been gained in terms of knowledge on the other hand is in any case worthy of documentation in a paper.

This paper will therefore detail the specific challenges of simulating the 1903 Wright Flyer aircraft in order that the simulation requirements are met.

Wright Flyer Simulator – Challenges of realizing a realistic synthetic environment

The challenge of realistic simulation has been the basis of research and development in this sector during its first 75 years. Reproducing the environment encountered by the pilot through synthetic representations of that environment continues to pose several challenges. Simulation technology has evolved over the years as an inexpensive and controllable means of training pilots, as well as a reproducible medium for conducting research. Today's simulators are capable of simulating most aspects of the flight environment, however they deal mostly with vehicles with known flying qualities and stable systems (or for fly by wire aircraft the stability has been enhanced).

When the vehicle dynamics are both unstable and not fully described, the situation becomes quite different. The Wright Flyer is a good example of a system whose dynamics were known to be a problem. The vehicle had severe pitch instability, as well as lateral (spiral-mode) instability, Fig. 1. The presence of a rudimentary and first-generation control system made the problem worse: The pitch controller was a small stick, controlled by the left hand, while lateral control (wing warping and linked rudder) were mechanically driven by a hip cradle. Furthermore, the aeroelasticity of the vehicle did not simplify the problem. Finally, the prone position of the pilot, although offering lower drag, made flying

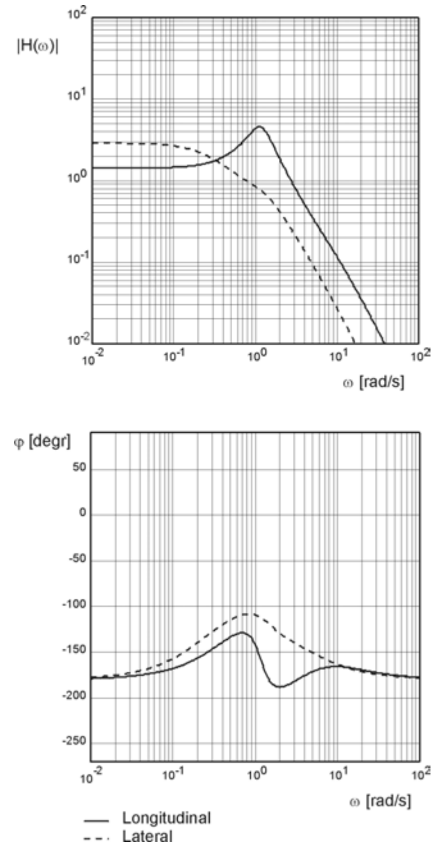


Figure 1 – Longitudinal and Lateral Dynamics of the 1903 Wright Flyer.

somewhat cumbersome. It is therefore noteworthy that the Wrights were not only the first to fly, but even managed to fly perhaps one of the most difficult to control vehicles in the past one-hundred years.

The Wrights primarily exercised their skill-based control behavior when flying their airplane. Rasmussen (1983) has defined three such levels of behavior – skill-based, rule-based and knowledge-based. Skill-based behavior deals with the continuous manual control of the system and is dependent upon the flow of real-time signals. Key to the stabilization of a vehicle are the visual and non-visual motion cues, which have been shown to be directly coupled to the pilot's skill-based behavior. Secondly, rule-based behavior deals with signs marking changes in conditions, which force the pilot to select new procedures or rules. Finally, and on a more abstract level of functional reasoning, knowledge-based behavior which deals with symbols and is based on the cognitive understanding of the particular task.

The pilot perceives and controls the motion of a dynamic vehicle through various sensors, including the visual, vestibular, somatosensory, proprioceptive and the audio systems. The pilot makes use of these sensory outputs in two ways. Firstly, for his skill-based control behavior in the inner attitude control loop, he tries to make optimal use of the available information. Secondly, for his rule-based and knowledge-based behavior, he needs to integrate the sensory outputs in the more complex motion perception process on how he and his aircraft is moving in the environment to be able to make the right choices and decisions.

If the reproduction of the skill-based control behavior is critical to simulating a vehicle, then it is imperative to first understand what parameters influence that behavior within the real vehicle. In this particular case of the unstable Wright Flyer the manual control characteristics of the simulated aircraft needs to be representative. Following this, the simulator can be designed using only the required functional capabilities as guidelines, rather than being dependent upon technological solutions. In this way, the requirements of the simulator are based on an objective process rather than guesswork. What does, however, make this challenging is gaining the capability to predict the pilot-vehicle interaction in the real vehicle and in the simulator. For this, we need to turn to mathematical modeling of the pilot in his control task.

The aim was to use a pilot model to optimize the motion simulation. Since the motion system of a simulator stimulates the vestibular system primarily, one could attempt to define the simulator requirements by a pure mimicking the vestibular stimulation alone. However, in reality, we use a number of sensory inputs from which the visual and the vestibular are the most important in vehicle control, integrated together, to generate the control output and perceive self-motion. We do not distinguish then the information coming from the various sources. Moreover, only mimicing the vestibular stimulation lead to large requirements for the motion space, since they do not take into account the significant impact of the visual environment in perceiving motion.

A number of mathematical models have been developed aimed at describing a pilot's skill-based control behaviour [5, 6] and taking visual and motion feedback into account [7, 8] has developed and successfully applied a model to predict pilot-vehicle behavior in skill-based control tasks. In this model all available knowledge on the sensory systems, neuromuscular system, and processing delays are incorporated. Adjustment of the model to the vehicle dynamics is obtained by a small number of gain parameters weighing the sensory outputs. The model is adjusted with an optimization procedure taking control performance, control effort, and the loop stability into account. The thus described pilot behavior is the reference when defining the motion cueing system (washout and motion base). The aim of this definition process is to maintain pilots control behavior in the simulated aircraft as close as possible to the real aircraft. (By coupling the vehicle dynamics to the pilot perception and control model, one can determine the gains that the human pilot needs to apply to inputs of his visual and vestibular system in order to achieve the required stability. This becomes then the fixed state to which the simulator can then be defined. The process is explained in more detailed in prior work [4].

A Systematic Approach to Simulation Requirements

This project was aimed at designing a simulator that would replicate the control behaviour by the pilot. By utilizing the above process, one can arrive at an objective specification of the simulator. However, the question that needs to be addressed is whether this meets the objectives.

For the specification of the training media, it is necessary to first specify the training ***objective*** (the level of proficiency that the trainee has to master following the training), and the training ***need*** (the difference between the *objective,* and the proficiency *before* the training). If the design of the training media is based on such a specification, then its characteristics must still be defined. In other words, how much of the requirement must be fulfilled, and what compromises are acceptable?

Currently, simulator design follows a rather empirical approach. Depending upon the application, the techniques applied may vary slightly, however the general tendency is to make use of available technologies in conservative ways. Take for example civil training simulators, whose qualification to a certain standard is critical to the customer's requirements. Meeting these standards – which were themselves established on the basis of technological possibilities, rather than quantifying and matching the pilot behavior in the simulation to that in the aircraft – is therefore the only technical criteria. Furthermore, the relatively low volumes of flight simulators (averaging around 50 devices worldwide per year) do not allow much room for technological revolution, due to the high non-recurring costs. The technologies in simulation are therefore driven by a market opportunity approach, rather than finding the most creative and effective solution. If a solution tends to have parameters that are not within the tolerances of the civil regulatory guidelines, then it will be very difficult to incorporate the change, no matter how much better it is.

Despite the fact that knowledge and technologies are available, few are able to take full advantage of these.

Qualification to the status quo often predominates over finding the best training solution.

In this particular instance, the situation is different: There are no real qualification requirements, and there is no aircraft with which qualitative evaluations or comparisons can be extensively carried out. No person today has a feel for the flying qualities of the Wright Flyer. Yet, if building a simulator, one would want to resort to affordable solutions with little financial investment is possible. It is this problem that made this project an invigorating one, and a model design exercise for creative simulator design.

In 2002, Advani and Hosman showed the use of the latter's pilot model in developing the basic motion cueing requirements. First, the pilot model will be briefly explained, and then the requirements generated by the pilot model are further analyzed in order to specify an integrated simulation system.

The descriptive pilot model developed and validated [7, 8] by Hosman, is aimed specifically at piloted control tasks involving tracking and disturbance motions. The model can describe the influence of the visual and vestibular stimulation induced by the aircraft motions on the pilot's control behaviour. The final model is depicted in Figure 2.

In this model, the human motion sensors - each of which is described by a transfer function - are placed in parallel and convert the stimuli (the attitude, angular rate, and angular acceleration) to the sensory outputs $R_i(\omega)$. The differences in sensor dynamics are due to the fundamental differences between the visual and the vestibular system: The visual system is position and rate sensitive, while the vestibular system is sensitive to angular accelerations and specific forces.

Adjustment of the pilot model to the vehicle model requires the adjustment of parameters in a cost function.

When a pilot adjusts his/her behaviour to a certain control task, the first objective is to achieve an acceptable level of tracking performance. However, if the pilot would try to minimize the tracking error alone, his control actions would not be taking into account the aircraft characteristics, structural loads and passenger comfort, for example. In reality, the pilot will normally consider putting more effort into the task as a function of the benefit of the resulting performance improvement, and relative to the corresponding increase in workload.

Furthermore, as a pilot tries to improve tracking performance, he will also increase his gain. This will result in an increase of the crossover frequency ω_c and a decrease in phase margin φ_m. A gain that is too high will reduce the stability of the control loop. So, the choice of the cost function should aim at the following:

- Good tracking performance
- Effective control effort
- Adequate bandwidth and stability of the control loop as expressed in the crossover frequency and in the phase margin

In order to achieve these goals, the following cost function can be applied.

$$J = \Sigma(e^2 + Q.\delta^2 + R.\dot{\delta}^2) \qquad [1]$$

Where e is the tracking error, and δ is the control output. The weighing factors Q and R in the cost function depend primarily on the aircraft characteristics, and on the task to be performed, i.e. the disturbance or maneuver task.

Task Dependence

The use of these signals is also dependent upon the task requirements. One can distinguish between two tasks – a tracking task, where the pilot compensates for errors

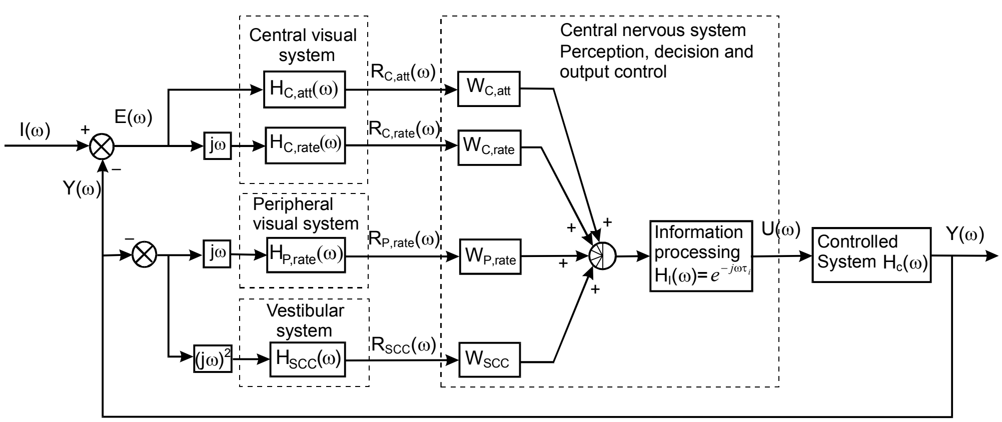
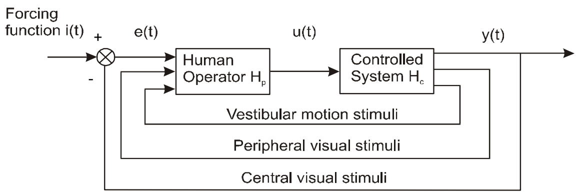
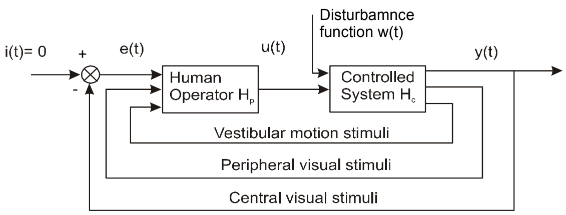


Figure 2 - Block diagram of the descriptive pilot model in the maneuver task.

(perceived primarily through the central visual system), and disturbance rejection tasks. See Figure 3.



a. Maneuver task



b. Disturbance task

Figure 3 - Differences in the influence of motion feedback in the maneuver task and the disturbance task

In disturbance tasks, the pilot receives changes in the motion of the vehicle, which are fed back directly through the vestibular system. It has been shown that motion plays a critical role in vehicle stabilization during disturbance tasks, and a more supporting role in tracking tasks. The aircraft dynamic characteristics play a most significant role in the tracking task. In the simulation of an unstable vehicle as the Wright Flyer, the pilot should be able to generate control inputs in the simulator that are representative to those in real flight. This would maximize the value of the simulator.

Once the pilot model is coupled to the vehicle model, one can adjust the pilot model systematically to stabilize the system. When this is state achieved, the system is frozen. Then, the closed loop is extended, Figure 4, incorporating the typical simulation characteristics, time delays, washout and visual and motion base system characteristics. The original cost function, which is considered to be representative for pilot's control strategy, is used to optimize washout algorithm parameters. After the washout is optimized, the pilot model is readjusted to the simulated aircraft to check if the changes in the pilot model are acceptable. Otherwise the procedure is repeated. (the pilot model must be re-adjusted to that situation.) If one can achieve the same conditions with the simulation systems as before, the fidelity will then be equal.

Note that the pilot model is sensitive to the motion and visual information, and also to the temporal fidelity of the closed loop system. The model-based analysis of the closed-loop system, in fact, gives us information on the control engineering aspects of the closed-loop system, including the following:

- Motion cueing algorithm
- Motion system response
- Simulation time delay of the real-time system
- Time delay of the visual display system

Simulating the 1903 Wright Flyer

As mentioned earlier, the Wright Flyer demonstrated unstable dynamic behaviour. Figure 5 shows the results of coupling the pilot model to the simulation of the Wright Flyer. Four configurations are shown;

- Real aircraft with visual feedback only,
- Real aircraft with visual and motion feedback,
- Simulated aircraft with classic washout filters,
- Simulated aircraft with the optimal washout filter.

The pilot model has been adjusted to the Wright flyer dynamics so that maximum stability was achieved. (crossover frequency ω_c = 3.7 rad/s and phase margin φ_m = 41°) By optimization of the washout filter, this bandwidth and stability could almost be maintained (crossover frequency ω_c = 3.5 rad/s and phase margin φ_m = 29°)

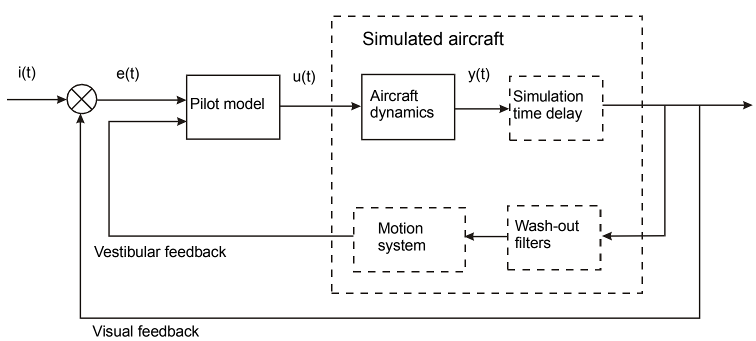


Figure 4 – Closed-loop manual control in a simulation environment, showing most prominent contribution of simulation to the closed loop.

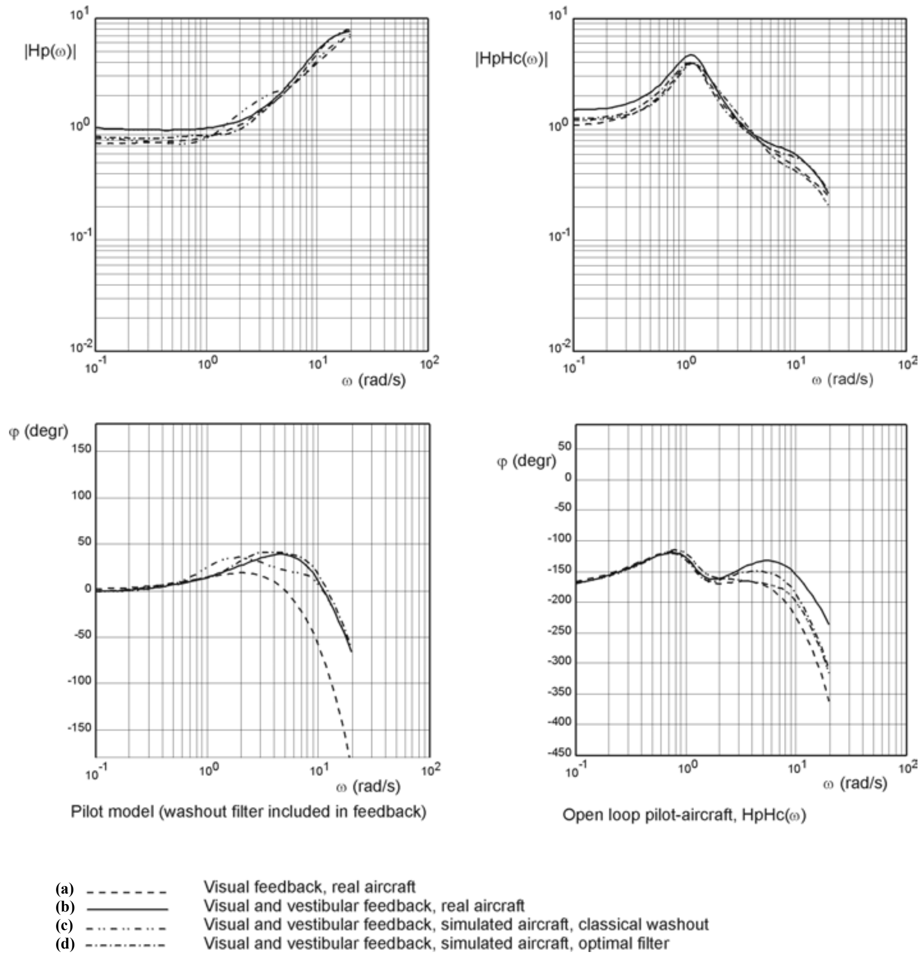


Figure 5 - Bode plot of the pilot model and the pilot-aircraft open loop for the Wright Flyer in the disturbance task. Real aircraft with (a) visual and (b) visual and vestibular feedback, simulated aircraft with (c) classical washout and (d) optimal washout.

Flight Control System Simulation

From this analysis, it was clear that the control of the simulated Wright Flyer would be (so) difficult and could result in crashes rather than successful attempts. Not only the control forces would have to be simulated, but also the aeroelastic effects.

Simulating the control feedback of the Wright Flyer is extremely important in creating a realistic pilot control output. The vehicle instability makes this a challenging problem. There were several ways of dealing with this problem. The vehicle dynamics could be adjusted in order to improve its handling qualities. This, however, forces significant deviation from reality. In a demonstration project like this, this would be highly undesirable, since it was the aim to maintain the original characteristics in order to demonstrate its challenges. Instead, one could introduce a stability augmentation system into the control loop. Then familiarization with the virtual Wright Flyer could be obtained without the drawback of the controllability problems, while as a pilot would gain experience with the system, the level of augmentation could be gradually reduced. The last option was selected, due to its relative merit, and the ease of implementation.

A feedback controller, augmenting the stability of the aircraft, could improve handling qualities considerably, without changing the aircraft inherently.

The classical root locus feedback controller design method was applied, to remain in style. The following feedback variables have been assumed:

- Symmetric motions:
  - Angle of attack
  - Pitch rate
- Asymmetric motions:
  - Sideslip angle
  - Roll rate
  - Yaw rate

The control inputs available are:

- Canard

- Wing warping combined with rudder (as applied by the Wright Brothers)
- Separate rudder (not applied by the Brothers)

Initially, the controller design was performed separately for symmetric and asymmetric motions. A linear model was obtained in three operating points: at design speed, 5 kts above and 5 kts below. The linear model was distributed over symmetric and asymmetric partial models. Feedback controllers were designed for both parts. During subsequent evaluation by simulation, with the feedback controllers connected to the complete linear model, a very unstable behaviour was observed. Apparently, cross coupling between symmetric and asymmetric motions cannot be neglected. From then on, controller design was applied to the complete linear model. A stable behaviour was possible in all three operating points. Considerable cross coupling was observed, however, especially from an input at the canard to the lateral variables.

The feedback controller consists of a mere gain matrix. In order to effectuate the control, three actuators have been assumed, each having a modest bandwidth of 5 rad/s. To facilitate interpolation between gain matrices, for in-between operating point operation, care has been taken that gain matrix elements will not change sign between adjacent operating points, which might turn a gain to zero inadvertently. As the root locus method may result in multiple satisfactory solutions, this could happen otherwise. A deliberate reduction to zero of an element is acceptable, however.

The root locus design procedure is a single-input, single-output method, whereas the underlying case is explicitly multi-input, multi-output. Therefore, the procedure is repeated quite a number of times, alternately for symmetric and asymmetric output variable/input combinations. Cross combinations were not applied, as no physical justification was felt for this. The apparent cross-coupling is merely seen as incidentally. It was pursued to move the unstable eigenvalues little-by-little to the left half of the complex plane, at the cost of feedback gain increments as low as possible. Typically, about 20 to 25 repetitions were required for one gain matrix in this case.

The 'Sisotool' from the Matlab Control Toolbox was applied. A Matlab script has been written to deal with the subsequent repetitions, mainly to structure the process and to keep it tractable and reproducible. The effects on the root loci due to feedback are illustrated in Figure 6 and Figure 7, respectively, before and after the design process.

Note that although new motion drive filters were not re-calculated following the specification of the stability

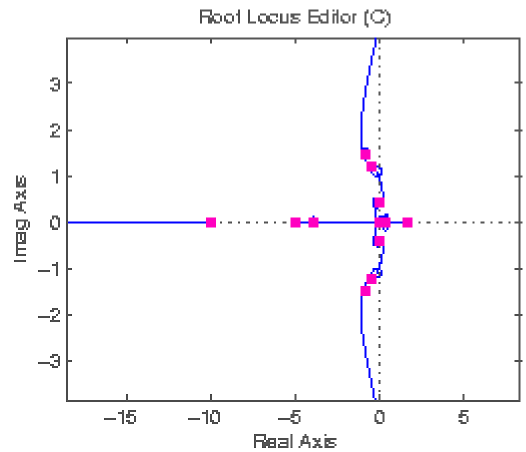


Figure 6 - Root loci without feedback

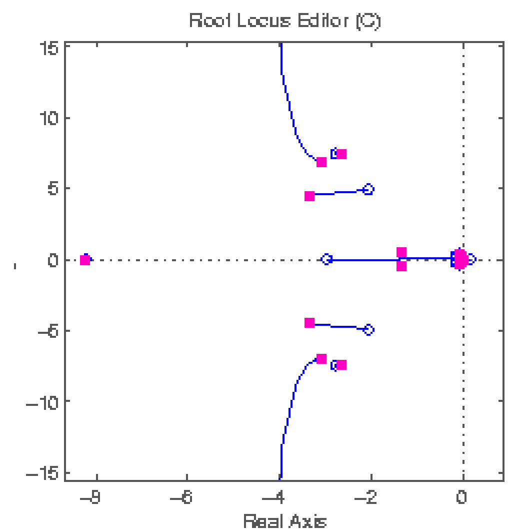


Figure 7 - Root loci with completed feedback gain matrix

augmentation system, this would be an important step in this systematic process.

Simulator Design Specification

The above analysis followed a closed-loop approach utilizing the pilot model as a focal point. From this apriori information, it became possible to specify the systems, and to receive validation information in advance. This process of "simulating the simulator" led to a design specification that was challenging and innovative.

Motion

When specifying a motion system, one can use a number of approaches: First of all, it is possible to use the standards published by regulatory authorities. These stipulate the excursions, the latency, the bandwidth and the cross-coupling objectives that must be met in order to qualify the system to a particular standard. These parameters do *not* specify the motion cueing properties. Usually, the cueing quality is adjusted later on – after the system is built, through an experience-based heuristic optimization process.

The method shown above leads to a set of motion cueing parameters that will maintain the aircraft flying qualities as closely as possible in the simulator, without the implicit need for heuristic tuning. While these parameters do not include transient effects (touchdown bumps, buffet, runway rumble), these special effects can be added later on.

Closely related to the motion cueing parameters is the simulator motion envelope. In the ideal situation, one would want the simulator to move throughout the envelope commanded by the optimized washout algorithm without any characteristics of the motion system mechanism coming into play. These characteristics are (a) the motion envelope, (b) the time delay and (c) the smoothness of the system.

Motion envelope is currently not specified by simulator regulatory standards. At the most, these standards specify the single degree-of-freedom excursions of any point on the simulator. The prior analysis was actually developed on the basis of visual and vestibular perception, suggesting that the motion envelope resulting from the trajectories generated by the washout should be created for the reference point at the pilot head. In a hexapod-type motion system, this is not always easy to achieve: The maximum motion envelope is actually at the centroid of the upper gimbals, and requiring motions at the pilot head dictate careful consideration of the geometric solution. For example, if a pitch rotation is commanded at the pilot head in a simulator with a large vertical offset between the upper frame of the hexapod and the pilot, then the motion platform must receive translation and (pitch) rotation commands. In normal hexapods, this tends to significantly reduce the available envelope.

Advani [9, 10, 11] suggests a method of specifying the motion envelope that is more thorough than stating the single-degree-of-freedom excursions. The excursions are cast into a "hyper-ellipsoid" whose major axes represent the weightings of the various degrees-of-freedom (Equation 2). This ellipsoid can then be either scaled to fit into the available motion envelope, or the envelope itself be adjusted in order to accommodate the required hyper-ellipsoid.

$$\overline{X}^2 + \overline{Y}^2 + \overline{Z}^2 + \overline{\psi}^2 + \overline{\theta}^2 + \overline{\phi}^2 = R \quad [2]$$

Here, R is the weighted radius of the hyper-ellipsoid. $\overline{X}$, etc are the generalized coordinates, denoting scaled, non-dimensional distances from the platform's neutral position (denoted by *n*). For example,

$$\overline{X} = \frac{X - X_n}{\rho_x} \quad [3]$$

Here, ρ_n indicates the weighting factor for the X-axis of the hyper-ellipsoid.

When a hyper-ellipsoid is used, it provides a better representation of washout-generated simulator trajectories.

Latency

The computational processes, hardware, software and the mechanical systems generate latencies in the simulator motion system. They can be defined by time beginning when the command data is available from the simulation host computer, and ending with the physical onset of acceleration. The pilot has to compensate for these latencies by applying a lead in order to increase his phase margin at the crossover frequency.

While current standards for flight training simulators sipulate latency limits of 150 milliseconds, this is again based on technological capabilities. In fact, some may argue that since it is difficult to prove exactly how much latency is acceptable, that the latency tolerances may even be relaxed in order to achieve higher scene content in the visual system.

In the mathematical model described earlier, it is posible to investigate the effects of time delays on the pilot performance in closed-loop control tasks. Our analysis of the Wright Flyer simulator was based on a total latency of 70 ms. In the analysis, it became very clear that the stability was highly dependent on the amount of latency present.

Bandwidth and frequency envelope

Latency has a direct influence on the closed-loop system characteristics, hence, the bandwidth and stability of the closed-loop system. Depending upon the simulation requirement, bandwidth may play a more important role than even workspace. For example, in a highly unstable aircraft such as the Wright Flyer, it is critical to have an immediate response. If the amplitude is allowed to become high, the system is already unstable. Therefore, one must use care in developing a balanced motion system requirement.

The frequency response envelope describes the maximum and minimum allowable limits for the amplitude ratio and phase shift of a motion system response produced resulting from a sinusoidal command to the motion drive system, and as a function of frequency. This envelope can be specified for each degree of freedom, during the worst case at any combination of frequency and amplitude, and at any location within the specified motion system workspace.

Another advantage to the approach that we describe here is that the motion specifications can be based on real data. Figure 1 shows the longitudinal and lateral open-loop transfer functions of the Wright Flyer. The open-loop with the pilot model was shown in Figure 5. At the crossover region of the longitudinal Wright Flyer dynamics, the phase lag is approximately 180 degrees. In Figure 5, it can be seen that the crossover frequency is at 3.7 rad/s for the real aircraft. Clearly, this represents a challenge to fly for any pilot. If one is to specify the motion system bandwidth, then the bandwidth can be selected above 3.7 rad/s.

Smoothness

The smoothness of the motion system must be high and remain consistent regardless of turn-around of the direction of motion of the actuators. It must also be independent of the pose of the motion platform within its operating envelope.

Audible Noise

Motion audible noise should be minimized in any simulator. This can not only distract the pilot, but cause one to adapt to the motions of the simulator rather than of the aircraft. The measurement of the noise can, for example, be sampled at specified distance from any actuator during motions in a certain degree-of-freedom and at a pre-specified maximum velocity during a sinusoidal exercise.

Static and Dynamic Accuracy

The ability of the motion system to restore itself to the same reference initial position is termed the static accuracy. Dynamic accuracy refers to the system's ability to follow a specific trajectory throughout the workspace. Characteristic maneuvers may be used to determine how well a system performs with respect to these requirements.

Cross-Axis Coupling

The cross-axis coupling (or cross-talk) describes the maximum unintentional motion that can be expected in an un-commanded degree-of-freedom as a function of the motion of the commanded axis. This, like all the above, should also be tested within several reference poses within the workspace, rather than at every point.

Visual Display System

The type of operation, the flying task and the field-of-view dictate the basic visual display system requirements. In the case of the Wright Flyer, operations were always close to the ground. The pilot had phenomenal field-of-view (FOV) and used no instruments to determine the airspeed, altitude, rate-of-climb, etc. Additionally, the pilot lay prone and operated close to the ground, requiring large downward FOV. Stabilization requires much peripheral information. Type of operation requires high resolution. Update rate should be smooth, and delays low (due to instability of the aircraft).

In the latest revision of the Wright Flyer simulator design, a wide-angle real-image display was chosen. This partial dome, attached to the front of the pilot position, would provide a horizontal field-of-view of 150 degrees, and vertically 55 degrees upwards and 75 degrees downward. Projection with a UXGA LCD-type projector would yield sufficient resolution at the pilot eye point, and at an affordable price.

Control loads

The Wright Flyer's most peculiar system was the flight control concept. For the longitudinal motions, the pilot held in his left hand a rotating handle, like a single-axis side-stick. This drove a lateral torsion tube that was fitted with a bicycle sprocket gear, located on the right side of the pilot. The sprocket drove the bi-plane canard through a chain. Another peculiar aspect was the bending of the canard's ribs. As the angle of incidence was increased, the rib bending would increase, in order to mitigate the effects of stalling the canard. The mechanism also created a restoring moment to help center the canard control stick.

Lateral control was introduced through a hip cradle. As the pilot swayed his hips, a bellcrank-cable assembly would influence the wing warping and the rudder incidence simultaneously. Note that the wing warping took place only on the outer panels, where no diagonal inter-plane cables were present.

The elastic properties were modeled and implemented into the simulation of the Wright Flyer. The concept design included a two-axis electric control loading system.

Integrated math model

The mathematical model of the Wright Flyer (and other Wright aircraft [12]) has been operating at the University of Liverpool in conjunction with their full flight research simulator. The model is based on the NASA Ames wind-tunnel data, obtained from testing with a full-scale replica of the 1903 Wright Flyer. As part of

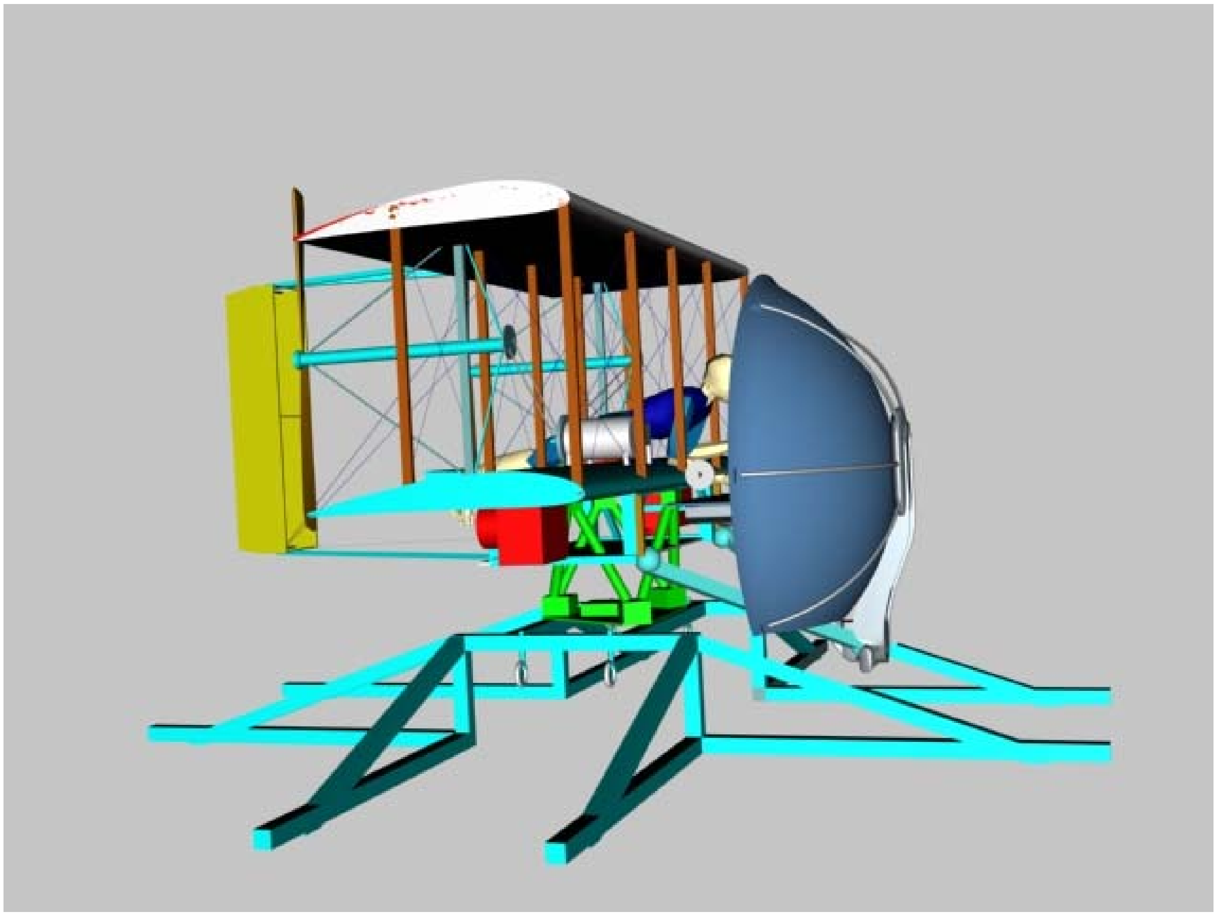


Figure 8 – Concept of the Wright Flyer Simulator. Note the large frames allowing transportability of the system.

this project, some additional features (aeroelasticity and control system) were incorporated. The model operates under the ART real-time FLIGHTLAB environment.

Resulting Design

Figure 8 shows the concept design of the Wright Flyer Simulator. This is intended for demonstrations and educational applications. Transportability is made possible by mounting the system on a folding frame. The presence of the wing center section enhances the realism of the flying experience, and the appeal of the simulator in general.

Discussion

The design of the Wright Flyer simulator has brought many interesting simulation design issues forward. Although the project has not met its destiny, it is clear that the process applied in the design, and even the design itself, have demonstrated a systematic approach to simulator design. Here are some of the most important findings:

In the specification of a simulator, it is necessary to specify the simulation objectives and the needs, before defining the simulation means. The former have to do with the type of aircraft and operations.

Human perception models can be utilized to objectively specify the motion requirements, as well as some of the properties of the total simulator itself (those related to control engineering). With the current models, it is possible to predict the influence of design parameters on the outcome. In other words, one can use these models to justify the investment and to identify risk. This can be a cost saving step in large simulator acquisition or design programs.

This approach is most important when cost is critical and performance criteria must be met. Even with standard off-the-shelf systems, this process can help eliminate areas of shortcomings that can later on not be altered.

Currently, we can predict the response of the simulator (mechanically). This is verification – is the simulator built to the specifications. With this approach, we can validate the simulator – does the simulator meet the training objectives?

In proper simulation design, it is not the technology of each sub-system that is the challenge, but realizing the desired level of performance from the integrated solution.

Conclusions

This paper has shown a forward approach to the design of a flight simulator representing the characteristics of a unique, unstable flight vehicle. Utilization of the principles applied here to other simulator projects can yield a clearer insight into the performance of the human subject in the simulator with respect to the target aircraft, and considering also the simulation objectives. This type of approach can help in the design or in the selection of simulation hardware and software. It represents a simulation-based design of simulators.

The ideas generated in this paper should demonstrate the benefits of this process, and to assert the need to additional research into motion cueing and perception. Particularly, the development and validation of more comprehensive human pilot models are necessary. For such developments, the stakeholders, including the builders, operators, researchers and regulators of simulation products should be willing to work together.

Simulation of the Wright Flyer has also increased our appreciation of the Wright Brothers as aeronautical engineers, and as pilots. They were reliant on knowledge obtained from observing bird flight and from building bicycles, and could not count on information available from predecessors. Some of the shortcomings in their design philosophy led to the unstable and challenging flying qualities of the 1903 Wright Flyer. As evolution has shown us, they only continued to improve the performance and handling of their machines after 1903.

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