



## **Design and Development of a Virtual Environment to Enable Interactive Teaching of Aircraft Flight Dynamics and Control Concepts (Work in Progress)**

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Dr. Gururajan's research interests are interdisciplinary and in the fields of fault tolerant flight control, parallel & distributed computing, real time systems, experimental flight testing using small UAS and UAS, and the design/development of natural language interaction with drones.

# **Design and Development of a Virtual Environment to Enable Interactive Teaching of Aircraft Flight Dynamics and Control Concepts (Student Paper)**

## **A. ABSTRACT**

Undergraduate students majoring in aerospace engineering are typically required to attend courses which are formulated around a traditional classroom approach, including lecture presentations and handouts, making the learning process monotonous and repetitive more often than not. This is particularly true even when discussing interesting but difficult topics such as aircraft dynamics, stability and control; students are expected to develop deep understanding while presented with material confined by the walls of a classroom. With recent advances in virtual reality (VR) tools – including inexpensive hardware and open source software, there is an opportunity to incorporate the use of virtual environments into this traditional course and bridge the disconnect between classroom material and realistic flight dynamics and controls. This paper outlines the development of a virtual reality environment to aid in teaching the design and evaluation of flight controllers using classical control techniques. This environment is being designed to provide a collaborative space where user(s) can manipulate the locations of poles and zeros of a controller for a dynamic system (such as an aircraft) and visualize its response. Such an environment will enable the user(s) to visualize how controller design choices directly affect an aircraft's performance in closed loop configuration.

**Keywords:** Virtual Reality, Short Period Dynamics, Classical Control Theory, Stability Augmentation System

## **B. INTRODUCTION**

The typical aerospace engineering undergraduate experience is generally filled with large textbooks, dense lecture material, and the occasional lab to supplement the theory learned within the classroom. However, as new interactive technologies such as Virtual/Augmented Reality, haptics, high fidelity modeling, simulation and visualization continue to evolve, engineering education is slowly making the transition towards a more technologically integrated classroom. As this transition continues, these technologies will begin to play a more important role in the development of young engineers, providing them with a platform to experience and retain information in new ways.

A majority of aerospace engineering courses consist of the traditional classroom approach made up of lecture presentations and handouts describing complex theory and ideas which sometimes becomes monotonous, repetitive, and often times difficult to comprehend. Then comes the end of term and students are expected to have gained a deep understanding of these abstract ideas based on few examples and problems sets derived from a standard textbook. For example, one course that is fundamental and found in every aerospace engineering curriculum that deals with a vast amount of complex material is aircraft dynamics, stability and control. This course introduces students to fundamental concepts used in the design, implementation, and safety of aircraft; in recent time, with the rise of autonomous drones such as those being proposed by Amazon, or those used in search and rescue missions, disaster response, law enforcement and surveillance to name a few. Therefore, learning and developing a deeper understanding of these concepts are even more relevant.

However, learning aircraft dynamics becomes challenging when confined to the information on the pages of a textbook. Aside from lengthy calculations and derivations of complex equations, the visualization of an abstract concept such as the dynamic response of an aircraft and the design and impact of flight controllers are difficult to conceptualize for students, and particularly so as they are typically exposed to material like this for the first time in their undergraduate studies. By taking advantage of the recent technological advances such as VR, it is possible to move towards a more “hands-on” pedagogical approach in this course; this could increase student engagement and encourage long term learning and retention of information.

In this paper we discuss the design and development of an interactive VR based tool to help in presenting advanced concepts to students in a new manner which would allow for a deeper understanding of challenging ideas and reinforce the theory learned from lectures, presentation and classroom handouts. In particular, we will focus on developing a tool to enable the design, development, and testing of a Stability Augmentation System (SAS) using classical control theory to augment an aircraft’s dynamic stability. This tool will utilize a open loop aircraft configuration in combination with the user’s ability to manipulate poles and zeros of a controller and visualize the resulting output of the dynamic system. This visualization approach will allow for testing and comparing various controller designs.

This paper is organized as follows: the overview of the virtual environment is discussed in Section III, followed by the specific design methodology for each of the respective subsections which make up the SAS. Section V discusses the envisioned implementation of the proposed methodology and testing of the stability augmentation system; in section VI, we discuss our vision for further improvements to this approach, testing and evaluation planned for the future.

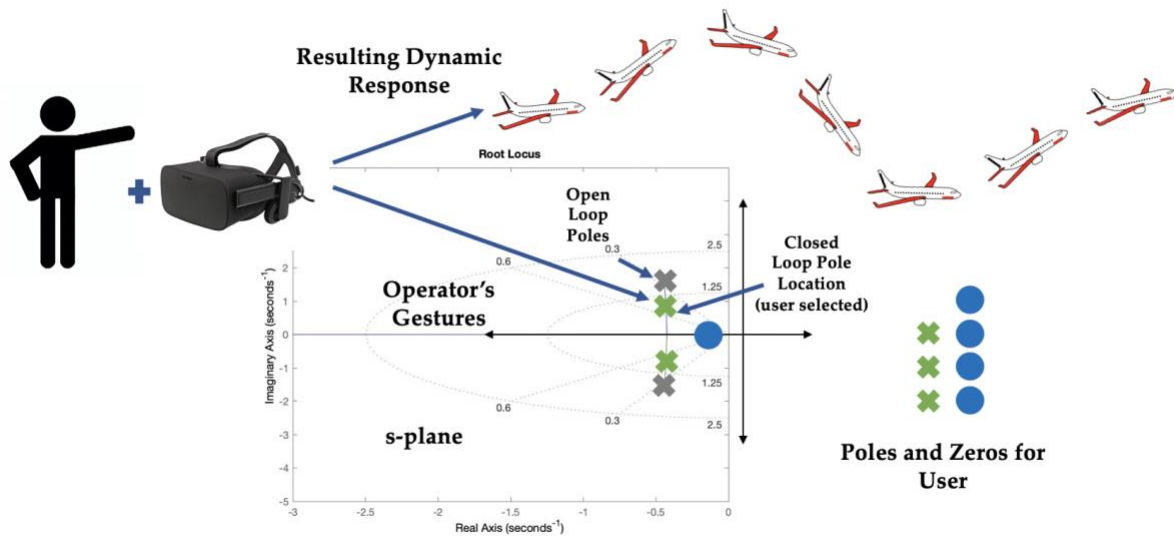
### C. OVERVIEW OF THE VIRTUAL ENVIRONMENT

The current design of the virtual environment is built around the model of a fixed wing aircraft – the model is viewable by the user in a default viewing screen and the corresponding mathematical model saved in the background. In this effort, we are limiting our focus to one specific dynamic mode of the aircraft (short period); within the virtual environment, the user will be presented with a pull-down menu that gives them access to the *s-plane* widget. This renders the *s-plane*, with the real and imaginary axes, and displays the open loop poles and zeros of the current aircraft model.

This window will display the poles of the current aircraft configuration and give the user the option to place additional zeros and poles to the system. This window will also give the user the ability to tune various gain values of  $K$  for each controller component. During this process the user inputs will be fed through to various control computations running in the background and calculate the resulting system open-loop and closed-loop dynamics. The user can then exit the window after setting the controller conditions and run the VR simulation.

This simulation will begin with the aircraft moving forward at a constant speed and level altitude representing the steady state assumptions necessary for the small perturbation equations to hold true. The aircraft will then experience an elevator step input exciting the short period dynamics and producing a short-term system response. At this point in time the user will be able to reposition themselves around the aircraft by moving their body position relative to the aircraft in their headset, giving them the ability to experience the system response from multiple different perspectives. This simulation will run for a set amount of iterations before returning to the default viewing screen where the user can update the controller configuration. A simplified overview of

the virtual environment and corresponding processes are represented in Figure 1 below depicting the user headset interactions and resulting visual output.



*Figure 1: A simplified representation of the Virtual Environment for Design and Evaluation of Aircraft Stability Augmentation Systems (SAS)*

#### D. OVERVIEW OF DESIGN METHODOLOGY

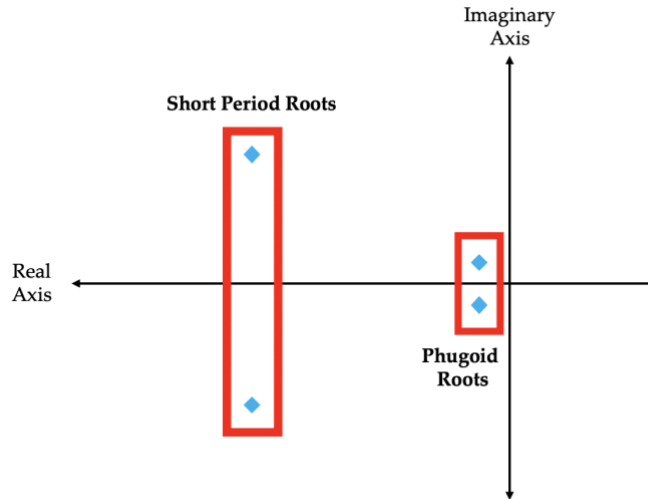
In this section, the various components utilized in the creation of a virtual environment to aid in the visualization of aircraft dynamics, stability and control are described. The virtual environment and the methodology followed here can be applied across other engineering disciplines to provide alternatives to aid in the understanding of abstract or difficult concepts. For this study, we focused on the dynamics of a fixed wing aircraft with a predefined mathematical model, selected a classical control theory approach to be implemented, and developed a means of testing and visualization for that approach.

##### A. Aircraft Dynamics

The dynamics of a fixed wing aircraft can be described by a set of non-linear equations representing the translational and rotational motion of the aircraft, when subjected to external forces and moments. These equations of motion can be broken up into two independent sets describing the aircraft's lateral and longitudinal motion. For the purpose of this study, we limit our discussions to the longitudinal dynamics and linearize the aircraft dynamics around small perturbations about a wings level, steady state flight condition [1].

The longitudinal dynamics of a fixed wing aircraft can be further split into two second order dynamics – short period and phugoid dynamics. The system poles which represent the longitudinal stability of an aircraft for each of the two modes described above can be found below in Figure 2. The short period response can be characterized by a rapid change in angle of attack  $\alpha$  and pitch attitude  $\theta$  and has direct implications on the dynamic stability of the aircraft as well as the handling qualities and pilot workload.

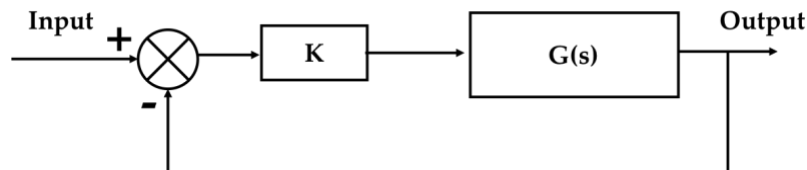
As the short period dynamics is considered to be of relatively higher importance than the phugoid dynamics, we chose this mode for further analysis.



**Figure 2: Pole locations describing the longitudinal dynamics of an aircraft**

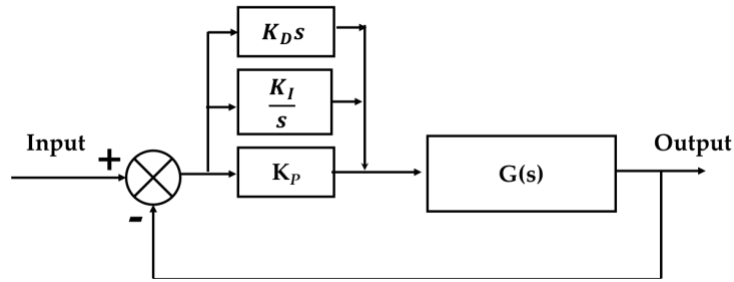
## B. Controller Design

Classical control theory deals with single input single output (SISO) systems in the frequency domain. Described below are the two types of controllers that is considered for implementation in this study, a Proportional controller and Proportional-Integral-Derivative (PID) controller. In the implementation of the Proportional controller, the error between the reference signal (or input) and the actual output of the system is used as the actuating signal for the aircraft longitudinal dynamics. A simplified schematic of this controller is depicted below in Figure 3.



**Figure 3: Architecture of a simple proportional controller**

Similar to the proportional controller, the PID controller utilizes a proportional gain,  $K_P$ , with the addition of integral and derivative gains ( $K_I, K_D$ ) in the feedback loop, along with appropriately located compensator poles and zeros. The derivative component helps in improving the transient response of the closed loop system, while the integral component helps in reducing the steady state error in the system response. With all three components (Proportional + Integral + Derivative) working concurrently, it is possible to improve both the transient as well as the steady state response of an aircraft's short period dynamics. A simplified schematic of this controller is represented below in Figure 4.



**Figure 4: Architecture of a simple proportional-integral-derivative controller**

Given the controller types described above, the user will be given the ability to manipulate the placement of poles and zeros which describe the location of the corresponding controller components. From here, the gain values associated with each component is calculated in the background and sent back to the VR environment for visualizing the resulting system dynamics. Additional outputs such as open-loop and closed-loop natural frequency and damping ratio, rise time, settling time, and steady state error will also be available to be displayed in the user's environment.

### C. Oculus Rift Virtual Reality Headset and Leap Motion Controller

The VR environment is being developed with the primary objective of building a tool to aid in teaching students the effects of different controller designs. Thanks to the wide availability and performance, the Oculus Rift headset was chosen as the user interface to the virtual environment. In addition to the headset, a Leap Motion controller was used to capture the user's hand gestures which would act as inputs in the VR environment. These hand gestures will include the manipulation of virtual objects representative of zeros and poles of the controller. Images and specifications of the Rift and Leap Motion controller to be used in this study can be seen in Figure 5 and Tables 1 and 2 respectively.



**Figure 5: Oculus rift Headset and Accessories [2]**

**Table 1: Specifications of Oculus Rift headset [2]**

Parameter	Description
Display	OLED
Resolution	2160 x 1200
Refresh Rate	90 Hz
Field of View	110 degrees

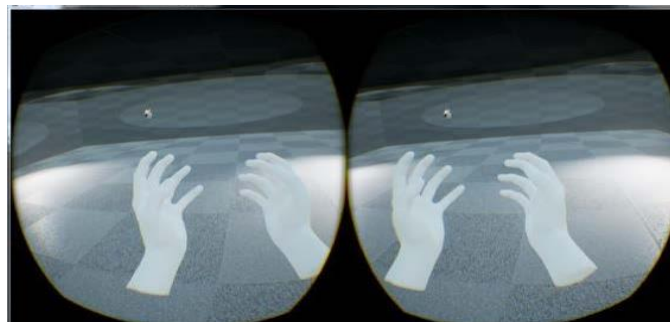
Tracking Area	5 x 11 feet
Sensors	Accelerometer, Gyroscope, magnetometer, and a constellation tracking camera
Requirements	NVIDIA GeForce GTX 960 / AMD Radeon Rx 470 or greater, Inter Core i3-6100 / AMD FX4350 or greater, 8GB + RAM

**Table 2: Specifications of Leap Motion Controller [3]**

Parameter	Description
Connectivity	Wired
Accuracy	±0.00039 in
Performance	200 reports/second

#### D. Virtual Scene with Unreal Engine

The virtual environment which was implemented within the VR headset was generated using the Unreal Engine 4 [4], a gaming engine development software created by Epic Games. The VR scene and program development were executed on a dedicated desktop computer (Intel i7, 32GB RAM, GTX1070). Within this VR scene, the Leap Motion plugin for Unreal Engine 4 was used to provide an accurate representation of the operator's hand gestures and movement. The location and movements of each finger on each hand were tracked and translated into the scene, when placed in front of the Oculus headset. The user's hands, rendered within the VR world, is illustrated below in Figure 6.



**Figure 6: Rendering of an Operator's hands within the VR Scene**

Through various gestures and operations within the environment, the user will have the ability to navigate the Unreal Engine heads up display and engage with classroom concepts in a new way. As demonstrated in previous research, similar gestures within a VR environment have been successfully used to enable flight commands/operations of drones [5,6]. We plan to implement a similar behavior in the development of our SAS, where students have the ability to immerse

themselves in a virtual environment allowing them to experience aircraft dynamics and control theory in a new hands-on manner.

### E. Design and Testing Methodology in the Virtual Environment

In this section, the process for how the open-loop and closed loop dynamics for a given aircraft model are calculated is described. This process uses predefined stability derivatives of an aircraft and equations representing small perturbation motion, around a steady state flight condition [7]. These values were imported into MATLAB and used to create an open-loop transfer function representing both the short period response for an aircraft’s angle of attack and pitch rate. For the purpose of illustrating the proposed methodology and analysis, only the transfer function representing the angle of attack was used to calculate the aircraft’s response to an elevator step input. This open-loop transfer function was then used in the development of a root locus providing the user with baseline stability characteristics of their aircraft represented below in Figure 7 with respective open-loop natural frequency and damping ratio in Table 3.

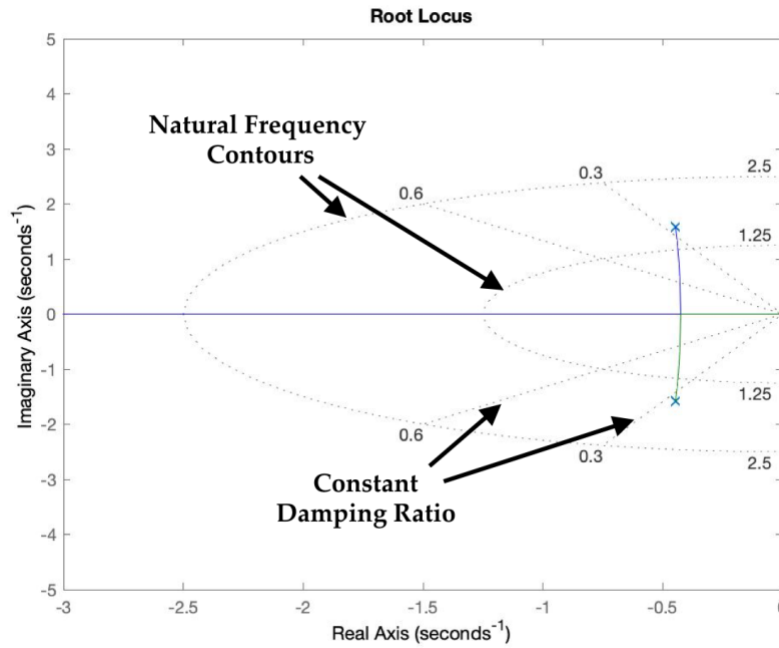


Figure 7: Root locus of representative 2<sup>nd</sup> order system, with desired natural frequency and damping ratio ranges

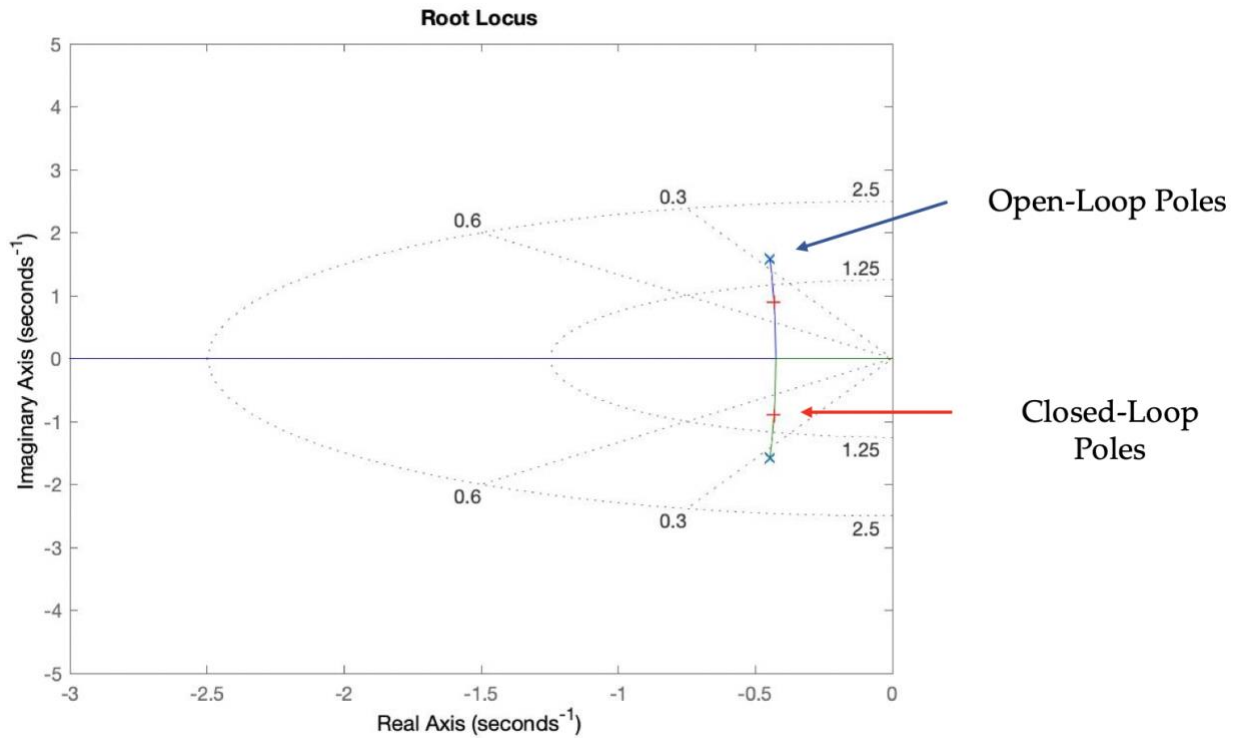
Table 3: System specifications of a predefined aircraft

Pole location	Damping ratio, $\zeta$	Natural Freq. $\omega_n$ (rad/s)	Time Constant (s)
$-0.446 \pm 1.58j$	0.272	1.64	2.24

With the ability to visualize the system poles on the root locus, the user can choose a new desired pole location which falls within their desired natural frequency and damping ratio ranges. In the case of a proportional controller, the valid pole locations are confined to the root locus. This input (user’s choice of desired pole locations) would be used to determine the value of the proportional gain  $K$ , which would move the system’s closed-loop poles to the desired location. An



example of this process is depicted in Figure 8 below, representing the user' of pole locations which fall within the desired natural frequency and damping ratio region in the s-plane. The resulting natural frequency and damping ratio, and the controller gain of the closed loop system is given in Table 4.

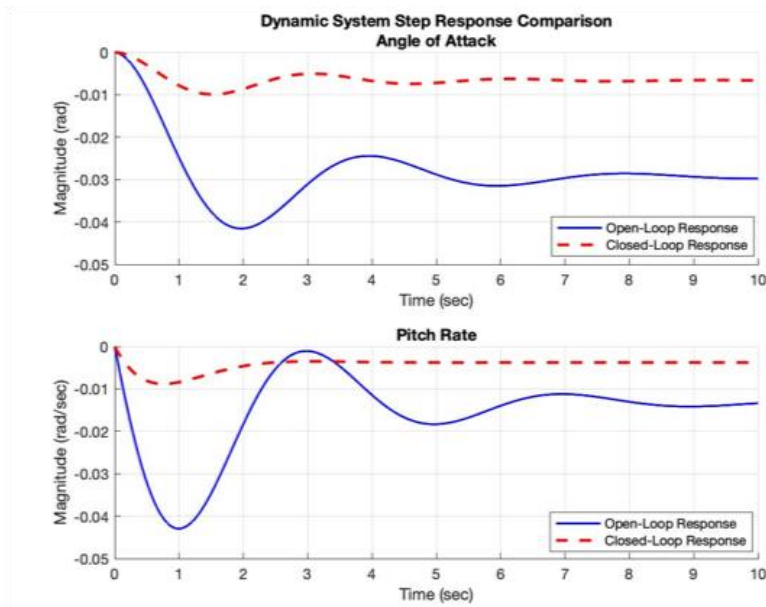


**Figure 8: Comparison of Open and Closed loop pole locations on the Root Locus of the representative aircraft**

**Table 4: Gain value and updated closed-loop damping ratio and natural frequency**

Pole location	Damping ratio, $\zeta$	Natural Freq. $\omega_n$ (rad/s)	Time Constant (s)
$-0.461 \pm 2.05j$	0.219	2.10	2.17

From these updated pole locations, the corresponding closed-loop transfer function can be calculated. This will then allow the user to compare the original open-loop response to the new closed-loop response. An example of this process and the corresponding system outputs is represented below in Figure 9.



**Figure 9. Comparison of open-loop and closed-loop systems dynamic response, from user input.**

These generated responses will be tied to the aircraft model within the user's headset and visualized in the VR environment. The implementation of other types of controllers will follow a similar methodology with appropriate changes in the calculation process and available user inputs.

## **F. Conclusion and Future Work**

By taking advantage of rapidly developing interactive technologies such as Virtual/Augmented Reality, haptics, high fidelity visualization, and modeling and simulation techniques and implementing these methods to aid in the understanding of complex concepts discussed within the classroom, undergraduate engineering students are given the opportunity to experience and understand classroom material in a new way. This paper outlined the approach being taken in the development of a VR based Aircraft Stability Augmentation System to assist in the fundamental conceptualization, application, and effects of controller design on an aircraft's dynamics. This tool can provide the user the ability to place/move and manipulate poles and zeros within the controller's design and visualize the resulting system response.

Currently this tool is being designed for a single aircraft configuration simulated at a single flight condition. Future development of this tool will give the user the ability to choose between various aircraft configurations and models which can be simulated at different flying conditions. Additionally, this tool is planned to be implemented into an aircraft dynamics, stability and control course in the near future. Students taking the course will be asked to take part in a survey regarding their understanding of material and how it is affected by the use of this VR environment. Data and student feedback from this classroom implementation will be used for additional improvements in the future.

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