METHODOLOGY FOR MOTION BASE SIMULATION OF CLOSED LOOP SUPERMANEUVERS ON A CENTRIFUGE SIMULATOR

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Abstract

A methodology for designing a closed loop motion simulation is discussed in this paper. This procedure is applicable to a centrifuge simulator as well as other types of devices which can produce both motion and visual fields. The key issues of coordinating the motion field with the visual simulation are discussed. Both systems are driven by the stick commands of the pilot, thus making it closed loop. The motion fields simulated are based on supermaneuverable flight trajectories where research is needed to investigate how these supermaneuvers influence the ability of a pilot to perform a mission. The study of supermaneuverability is, indeed, an important area of research for the Air Force. It has been shown in performance studies that an agile aircraft has a definite combat edge over a nonagile aircraft. Also, using agility, a tactical maneuver can be performed expending less overall aircraft energy [1,2].

Introduction

The study of closed loop supermaneuvers on a centrifuge motion simulator opens up various areas of research in this area. Supermaneuverability refers to unorthodox flight trajectories [3,4,5,6,7] presently being investigated with high performance aircraft. It can be accomplished by at least four known methods: using a high angle of attack ($\alpha > 50$ degrees), thrust vectoring, vortex manipulation for control, or possibly using differential deflection of stabilizers or canards. Presently most supermaneuvers have been flown only with 1/7th. size prototypes [2], but the "Cobra Maneuver" has been demonstrated at airshows by both Soviet and U.S. high performance aircraft [8]. The key issue involved with flying aircraft in these unusual scenarios is the obvious structurable, controllability, and stability problems that occur. The structural problems can easily be solved by performing these maneuvers at low speeds or high altitudes. If this procedure is used,

then vulnerability becomes a problem of concern because both speed and altitude influence how these maneuvers can be safely flown from a structures point of view. In [2] a class of all pitch and roll angles for an F-15 aircraft are defined (based on data from prototypes) for both controllable and stable flight. Recently [9] feedback controller design is being investigated to improve controllability utilizing thrust vectoring on FA/18 models to expand the envelope of performance of these aircraft.

Other areas of research in supermaneuverability include the quantification of agility via metrics [10,11,12,13]. Performance studies [1,14,15,16] have shown a substantial performance advantage when an agile aircraft flies versus a nonagile aircraft. The agile aircraft has, apparently, a quicker reaction time and more opportunity to produce a counter offensive. It was interestingly shown in [1] that the agile aircraft can produce the same tactical maneuver with less total aircraft energy expended.

The main issue of these studies involves the effects on pilots as they fly these maneuvers. Their ability to perform the mission, may be compromised and various disorientation effects may occur. At the Armstrong Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Ohio, a 3 axes centrifuge simulator exists which can be made to replicate the motion fields of the supermaneuvers. The motion field simulation of 3 known supermaneuvers (The "Herbst's Maneuver", "The Cobra", and the "Yo-Yo Turn for BFM") have already been simulated and are discussed in further detail in [17]. This paper will address only the issues of closed loop control of the centrifuge simulator during these simulations of supermaneuverable trajectories. The coordination of the visual field with the motion field are important issues brought out in this paper. To illustrate the simplest closed loop simulation, it is necessary to first discuss a basic example to show how to coordinate both the motion field and the visual scene.

Example 1- The Basic Concept

To simulate a motion field on a centrifuge simulator that will match up with a visual scene, we consider first a simple scenario to describe such a problem. Figure (1) illustrates such a simple scenario involving a target aircraft and a chase aircraft. Note both aircraft have the following assumptions:

- (1) Both aircraft are at an altitude of 10,000 feet,
- (2) Both aircraft have a velocity of 400 mph, and
- (3) Both aircraft have a constant distance between them of 2700 feet.

These assumptions can easily be relaxed in the latter examples. With these assumptions, however, this allows a very simple solution to this problem. There are four steps associated with the coordination of the motion and visual field to make the entire system closed loop.

Step 1- Generation of The Motion Field on The Centrifuge Simulator

The first step is based on the realistic motion field that can be generated by the centrifuge. The term Gs in figure (2) represents that acceleration component down the spine of the subject (a standard definition used in acceleration studies). The onset and offset rates ($\pm .5Gs/\text{second}$) in figure (2) are the maximum attainable from the centrifuge simulator used for this simulation. Figure (3) illustrates how the 3 axes of the centrifuge achieves this motion field by vectoring the cab outward as the arm increases in speed. Thus the vector sum of the gravity vector and the $\Omega^2 R$ acceleration combine to produce the desired Gs vector which appears down the spine of the subject. Thus the motion field in figure (2) can be accurately represented on the centrifuge. The next step involves the production of the two aircraft scenario to match the motion field.

Step 2- Making The Target and Chase Aircraft Scenario To Match The Motion Field

With reference to figure (1), it is desired to have the two aircraft scenario identically match the motion field already specified. Figure (4) illustrates the yaw, roll, and pitch axes of the aircraft. Figures (5a-b) represent actual turn radius versus Gs (centrifugal acceleration) and time and G required to complete a 180 degree turn. Based on the assumption of 400 mph speed, and a radius of $R_1 = 5400$ feet (2 G turn) and $R_2 = 2700$ feet (4 G turn), the scenario can be described as follows: The target aircraft will fly the motion trajectory in figure (2) if starting at time t_0 , it flies the smaller radius for 30 seconds (one full circle). After it completes the small circle, it transitions to the larger circle in a 4 second in-

terval. The target aircraft then flies the larger circle for $1/2$ cycle, and then transitions to the small circle. This process is repeated indefinitely. In terms of the body axes of the aircraft, the yaw angle is equal to the angular rate of the circle. e.g. for the small circle this would be $360/30 = 12$ degrees/second yaw angle. The pitch angle is zero degrees since the altitude is assumed to not change. To compensate for gravity (figure (1)), the $\Omega^2 R$ term is 2 G but the gravity is always 1 Gs. The aircraft rolls [$\tan^{-1}(2/1) = 63.4$ degrees] to the left. This produces a total Gs (down the spine of the subject) of $\sqrt{2^2 + 1^2} = 2.24$ Gs. For the tight (4 G turn), the roll angle advances to [$\tan^{-1}(4/1) = 75.9$ degrees]. The total Gs is $\sqrt{4^2 + 1^2} = 4.12$ corrected to gravity. The roll transitions between onset ($+ .5Gs/\text{second}$) and offset ($- .5Gs/\text{second}$) can be assumed to change linearly. Figure (5a,b,c,d) illustrate the coordination of the motion fields with the yaw, roll, and pitch of the aircraft axes. The description of the visual field can now be presented quite briefly.

Step 3- Producing The Visual Scene

For most standard video graphics packages, the simulation of the visual field now follows straight forwardly. From Figures (6a-d), the roll, pitch, and yaw of the aircraft are known. In figure (1), the speed, altitude, and inertial frame are known. The distance between the aircraft is assumed to be constant at 2700 feet. This is all the information necessary to simulate the visual scene. The last step for this simple example is the characterizing of the stick controller to perform true closed loop response both in a visual sense and in a motion sense.

Step 4- Characterising Stick Response

To be truly closed loop, the pilot must pull back on the stick to change both the visual and the motion field simultaneously. Figure (7) illustrates in the pitch axis (the stick controls yaw motion in this case), only. Either a displacement or force stick could be used, however, assume the stick output (in one axis is $+ 10$ volts). For the yaw command, the stick gain is set such that $+ 10$ volts yields 12 degrees yaw/ second or a stick gain of 1.2 degrees yaw per second is used. This is for the visual scene only. The $+10$ volt stick output is then calibrated for the motion field at $10\text{volts} = .5G/\text{second}$ or $.05G/\text{volt second}$. This calibrates the motion field as per the stick commands. Thus as the pilot pulls the stick back, both the visual field changes (closed loop) and the motion field changes (closed loop). Since both motion and vision are coordinated with each other and the stick commands, the overall simulation is closed loop. It should be noted that if the pilot does not pull

the stick back to full deflection, he will lose the target on the screen. This is very similar to the real situation. This simple example now can be easily extrapolated to a more practical example.

Example 2- Expansion To A Realistic Dogfight

Figure (8) illustrates the expansion of figure (1) into a combat scenario similar to example (1) but with the aircraft not being required to be in constant turns. The calculations of the motion field remain the same; for the visual field, an alternating roll scenario results but the terrain path changes constantly with time. Now this procedure can be extended to any closed loop scenario.

Example 3 - Expansion To Any Combat Scenario

To extend this approach to any supermaneuver, the motion field of the target aircraft would be broken up into 3 body axis motion fields consisting of roll, pitch and yaw of the aircraft (denoted as $\Omega_R(t)$, $\Omega_P(t)$, $\Omega_Y(t)$). By taking a Fourier transform of each trajectory, one can first calculate (for the dominant frequency) a response similar to examples 1 and 2 described previously for only the dominant frequency. The procedure is then repeated for the next Fourier component etc. Then using superposition properties, the sum of the components to the motion simulation can be approximated by the sum of the commands to each fourier component. Figure (9) illustrates the Yo-Yo turn for BFM (Basic Fighter Maneuver) as actually simulated from centrifuge data and explained in further detail in [17].

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Figure (2) - The Motion Field Generated On The Centrifuge

Figure (3) - Principal of Operation of The Centrifuge

Figure (4) - Yaw, Roll, and Pitch Axes of An Aircraft

Figure (5b) - Time and G Required To Complete a 180 Degree Turn

Figure (7)- Displacement Stick and Display

Figure (8) - Lateral Translation For Example 2

Cab and Fork Commands

Empirical Data

Yo-Yo Turn Simulation on Centrifuge

Fork, and Cab Versus Time

Figure (9) - Yo-Yo Turn For BFM (Basic Fighter Maneuver)