Switched Motion Cueing Algorithm for Flight Simulator Upset Prevention and Recovery Training

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Abstract. Upset prevention and recovery training (UPRT) has been mandatorily required in the Level-D flight simulator by some civil aviation authority currently. Due to the limit motion capability of six-DOF motion platform, motion perception of pilot can’t be effectively satisfied with traditional classical motion cueing algorithm (MCA) during this kind of upset scenario training. In this paper, a switched MCA which optimized by GA was proposed. The switching mechanism ensured that MCA output optimal motion simulation signal to motion platform in different upset training phases. The motion command outputs, which may have sudden change during the transit of adjacent flight phases, were smoothed by a sigmoid function window. Simulation results showed that the proposed switched motion cueing algorithm had better motion replication performance and also made better usage for the motion platform’s workspace than the classical MCA.

Keywords: Motion cueing; Washout filter; UPRT.

1. Introduction

Loss of control in flight (LOC-I) has become the number one cause of serious flight accidents instead of Controlled flight into terrain (CFIT) over the last decade [1]. To improve the capability of pilots and flight safety, ICAO have released and updated a series of regulations about UPRT. And FAA announced that all of new flight simulators in US must have UPRT capability from March 12th, 2019 [2]. EASA also published new UPRT training rules, which have taken effect on July, 2019.

The UPRT training objective is to keep pilots have proper situational awareness during normal flight, and in the event of an upset, to apply correct actions to recover in time. Traditional Level-D flight simulators are lack of accurate aerodynamic model and motion capability to properly simulate the upset conditions, which are normally described as an unintentional pitch attitude of more than 25 degrees nose up, a pitch angle of 10 degrees nose down, bank angle of more than 45 degrees, or inappropriate airspeeds within above parameters [3]. Typical commercial aerodynamics database from aircraft manufacturers can only cover flight envelope within a small angle-of-attack region. The region outside the normal flight envelop have only extrapolated data which can’t be used to simulate the upset conditions with convincible fidelity. Therefore, aircraft manufacturers have to update their data packages to support the UPRT training demands [4].

Another big problem is motion perception. Upset conditions is always related to the large amplitude of aircraft attitude change. Since conventional Stewart platform is still the only option for Level-D flight simulator, the motion capability is limited to simulate the continuous acceleration. To meet the higher UPRT training demand, and at the same time, maintain current simulator hardware and training architecture, current motion cueing algorithm, which transforms aircraft motion to simulator motion,
need to be redesigned. J.N. Field and etc. [5] proposed a revised motion cueing architecture which incorporated workspace optimization and a new pilot perception model, as well as a stall buffet module to the classical washout algorithm. William W. Chung [6] analyzed the performance of typical washout filter with different motion parameters, based on two mild upset and recovery maneuvers. Shuk Fai Ko and Peter R. Grant [7] developed and tested a new adaptive motion cueing algorithm for UPRT. They found that for severe upset events both specific force and angular rate cannot be simultaneously at the same medium fidelity. Certain tradeoffs need to be made to minimize the false cues. Actually, in different flight phases of upset scenario, the motion perception target is quite different, so a unified motion cueing algorithm with tradeoff may not be attainable for all of the upset phases, or will lower the motion perception for every upset phase. In this paper, a switched motion cueing architecture is proposed. An individual motion cueing algorithm will be optimized only in the certain upset phase. Between different phases, a softly switched mechanism will detect phase change and ensure smooth motion feeling transition.

2. Classical Motion Cueing Algorithm

The classical motion cueing algorithm [8] transforms simulated aircraft motion into achievable motion of the 6-DOF Stewart platform. The inputs of algorithm consist of aircraft accelerations in translational channel and angular rates in rotational channel, and need to be transformed into simulator inertial frame first. Due to limited workspace of the motion platform, translational motion cueing need to combine high pass filter for the onset cues, and low pass filter to tilt the cockpit to provide sustained surge and sway specific forces. While angular motion cueing only provides onset cues with high pass washout filters.

Figure 1. Classical MCA for normal flight (right) and upset scenario (left).

The ‘tilt-coordination’ trick, which makes use of gravity vector to provide the feeling of low-frequent specific force for pilot, need to be carefully designed with limited tilt rate below human perception threshold, otherwise pilot will detect the artifact and ruin the fidelity of training in flight simulator.
For the classical motion cueing algorithm, the filter parameters have to be tuned with the worst-case aircraft motion so that the motion platform will not always push to the limit. But for the upset prevention and recovery training scenarios, this kind of tuning strategy will cause the mild motion feeling during normal flight phrase. Therefore, a possible solution is to make the motion cueing algorithm switchable according to different flight phases of UPRT. We can divide whole upset entry and recovery training into five continuous flight phrases [5]. For the low or moderate amplitude motion situations such as normal flight phrase and approaching to upset phrase, second-order translational high pass filters and first-order rotational high pass filters are enough to return the motion base back to its neutral position. While for the upset phrase with large amplitude maneuvers, third-order high pass translational filter and second-order high pass rotational filter need to be adopted. The relative scaling elements and filter parameters have to be optimized as well. This kind of switching architecture will realize nonlinear mapping between aircraft motion and simulator motion and make better use of motion-base capability, comparing with traditional motion cueing algorithm.

3. Optimization of Filter Parameters for Different Phases of Upset Scenario

For the current scenario-based training such as UPRT, every scenario has similar training flow such as normal flight, approach to upset, upset situation, upset recovery and then back to normal flight. Pilots’ motion feeling needs to be improved according to a bunch of flight curves from real UPRT scenarios. Every flight curve can be automatically divided into five flight phrases and parameters of motion cueing algorithm are optimized with individual flight phrase data. Then we will have different motion cueing strategy switched between different flight phrase.

![Switched MCA architecture](image)

Traditionally tuning of motion cueing algorithm is a time-consuming empirical job that may be influenced by different pilots’ subjective perception and always based on worst case scenario. Genetic Algorithm (GA) is a kind of widely used stochastic optimization algorithm, which mimics natural selection and evolution so that can generate optimal solution for all kinds of nonlinear systems with many variables. Its stochastic characteristic ensures that optimization process can escape from local minima that deterministic algorithm always encounters. Generations in GA are populations including individual chromosomes which can be updated with evolutional operators such as evaluation, selection, crossover and mutation at each iteration. The chromosomes with better fitness will have better chance to survive to the next generations. The chromosome, which used in the optimization of classical motion cueing algorithm, consists all of the key parameters in the high-pass and low-pass filters, such as cut-off frequency and damping ratio. The chromosome can be represented by:

$$X = (\omega_{hp}, \xi_{hp}, \omega_{lp}, \xi_{lp}, \omega_{hp\theta})$$ (1)
where $\omega_{hp}$ and $\zeta_{hp}$ represent cut-off frequency and damping ratio of translational 2nd order high-pass filter, $\omega_{lp}$ and $\zeta_{lp}$ represent cut-off frequency and damping ratio of tilt coordination 2nd order low-pass filter, $\omega_{hpr}$ represents cut-off frequency of rotational 1st order high-pass filter. This kind of washout filter configuration is for normal flight. The filter configuration for upset scenario is similar except that order of the translational and rotational high-pass filter is higher. Therefore, the chromosome for upset scenario need to be updated to seven elements.

The iteration process will evaluate the chromosomes’ fitness in every step. If predefined terminating criteria has not been met, the evolution process will repeat to find better parameters combination in a wide and complex solution space to minimize fitness function. The fitness function, which is designed to represent motion replication error and motion-base’s available motion capability, is defined and given as below:

$$
J = \sum_{i=1}^{n} \left( W_0 \int (f_a - f_s)^2 dt + W_1 \int (\omega_a - \omega_s)^2 dt + W_2 \int r_s^2 dt + W_3 \int \beta_s^2 dt + W_4 \int \beta_s^2 dt + W_5 \int \beta_s^2 dt \right)
$$

where the first two elements are for replicating the aircraft motion, the last four elements are for considering the motion capability limit of motion platform and returning cockpit to original point.

For every flight phase of UPRT, comparing with the tedious manual tuning of classical motion cueing algorithm, GA can automatically optimize motion cueing parameters for pre-collected flight training curves to balance the performance of motion replication and workspace usage. Houshyar Asadi [9] and Sergio Casas [10] previously have also adopted stochastic optimization algorithm such as GA and particle swarm approach to tune the washout filters. The main difference of our solution is that we segment the flight phrase, switch between them, and use multiple flight curves to optimize and improve performance of general upset scenario instead of single mission.

4. Softly Switched Design of Motion Cueing Algorithm

Within individual flight phase, the performance of motion cueing algorithm has been optimized by GA to better replicate aircraft motion. However, when aircraft states pass through different flight phase, the undesired switching effects will occur due to different order of washout filters and discrete filter parameters. Then the outputs of motion cueing show sudden discontinuities although the inputs run smoothly. This kind of hard switching will ruin the motion fidelity of flight simulator and make pilots feel uncomfortable and distracted from the normal training scenario. In this paper, a smoothly switching window is applied during the transition period of different flight phases.

The proposed switching mechanism is such that the two motion cueing algorithms run simultaneously and combine the outputs together with sigmoid functions to smoothly transit from one to another. A sigmoid function is a bounded differentiable real function that is defined for all input values and has a positive derivative at each point. The sigmoid function we use can be represented as below:

$$
S(z) = \frac{1}{1 + e^{-az}}
$$

where the parameter $a$ is a design parameter, which represent the fade-out speed.

The characteristics of this sigmoid function is that the output scope is from zero to one. And if we multiply this sigmoid function with each motion cueing output, we will get an average combination of both motion cueing output at the switching line. During the switching process, the combined motion cueing is accomplished using both old and new output simultaneously, and gradually faded out from the old one to the new one. The switching window is a design parameter, which depend on the parameter of $a$.

5. Simulation Results and Discussions

A typical pitch upset and recovery scenario [6] is used to evaluate the performance of the proposed switched motion cueing algorithm in MATLAB environment. The typical optimized parameters which is adopted in the washout filters for upset scenarios are computed by flight phase segmented GA-based solution.
Figure 3. Comparison of pitch rate and pitch angle from different MCA. Fig.3 shows the angular rate output and the angular displacement of motion platform. An ideal angular rate follows the real aircraft motion signal. The angular displacement is desired to be minimized to remain within the workspace limitations.

According to curves which are generated from the classical motion cueing and switching motion cueing in Fig.3 and Fig.4, the proposed switching algorithm has high motion fidelity in normal flight and approach to upset phase, and will decrease its performance during the upset phase. Comparatively, the classical MCA can’t change its behavior for different flight phases so that it will push the cockpit to the displacement limit when it has large amplitude upset inputs. The proposed MCA has the capability to make better trade-off between motion fidelity and workspace limit.

6. Summary

Within this paper an approach to smoothly adapt the flight phase of a motion cueing algorithm during UPRT is presented. The upset training scenario is divided as five phases according to the state amplitude of the aircraft. Within the individual phase, the performance of motion cueing is optimized by GA considering the tradeoff of fidelity and workspace. Between the adjacent flight phase, the switching effect is smoothed by a sigmoid function window. The advantage of this method is that the whole UPRT process can be optimized with segmentation of aircraft states instead of only with worst-case scenario. In the future, the switching mechanism can be further adapted to advance motion cueing algorithms such as adaptive MCA and model predictive MCA to more effectively make use of limited workspace and motion capability of motion platform.

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