Development of a Novel Low-Cost Flight Simulator for Pilot Training

Hongbin Gu, Dongsu Wu, and Hui Liu

Abstract—A novel low-cost flight simulator with the development goals cost effectiveness and high performance has been realized for meeting the huge pilot training needs of airlines. The simulator consists of an aircraft dynamics model, a sophisticated designed low-profile electrical driven motion system with a subsided cabin, a mixed reality based semi-virtual cockpit system, a control loading system and some other subsystems. It shows its advantages over traditional flight simulator by its features achieved with open architecture, software solutions and low-cost hardware.

Keywords— Flight simulator, mixed reality, motion system, control loading system.

I. INTRODUCTION

THE use of flight simulators for initial and recurrent pilot training by major airlines is universal, and its effectiveness is well recognized. However, the availability of flight simulator resources is too limited to meet huge training needs of all airlines due to high purchase cost, deployment cost and per hour usage cost of traditional flight simulator. Airlines are seeking affordable flight simulators [1], which can cover certain training tasks, to be a kind of substitution for traditional flight simulators. To meet these demands, some efforts have been made [2-4] to develop low cost flight simulator and similar training devices.

Recently a novel simulator named "light flight simulator" (Fig.1) is developed by our laboratory. The design philosophy of the novel flight simulator is quite different from that of the traditional flight simulator. To reduce its cost and weight, simulation devices of light flight simulator are heavily simplified by adopting several new technologies. The mixed reality technology [5] is used to construct a semi-virtual cockpit system which has realistic tactile feeling by equipment of true instruments, and also realistic stereo visual feeling by computer synthetic scenery and helmet monitors. That will tremendously reduce the overall weight, volume and cost of the visual system and simplify the simulator cockpit design. Purely electrical driven technology is widely applied in the motion system and the control loading system, which reduces the cost and eliminates the noise and pollution problem that conventional

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hydraulic system always brings. And a sophisticated designed low-profile 6-DOF motion platform can make the whole simulator system accommodate in common office room, while the traditional flight simulator need a dedicated three storeys high building to place. Furthermore, many functions which generally fulfilled by hardware modules in traditional flight simulator are partially substituted by well designed software modules. This measure improves reliability and maintainability of the complex simulator system and reduces a lot of construction costs.

Fig. 1 The novel flight simulator

This paper will first describe the architecture of the novel low-cost flight simulator, then discuss the design and specific function of several main parts of the simulator including aircraft dynamic model software, motion system, cockpit system, control loading system, and etc.

II. ARCHITECTURE OF THE NOVEL FLIGHT SIMULATOR

The overall architecture of the novel low-cost flight simulator is reported in fig.2. The core function of flight simulator is to provide realistic feelings including visual, tactile, force, auditory and vestibular feelings for trainees, so structure of the simulator can also be expressed by this principle: The visual subsystem provides visual cue. The cockpit subsystem including all instruments provides tactile cue. The control loading subsystem provides force feedback. The motion subsystem provides vestibular cue. The acoustic subsystem provides auditory cue. The communication subsystem connects all the system while the control console is the visual output of the status of the simulator. And the aircraft dynamic model drives all other subsystems and connects them.

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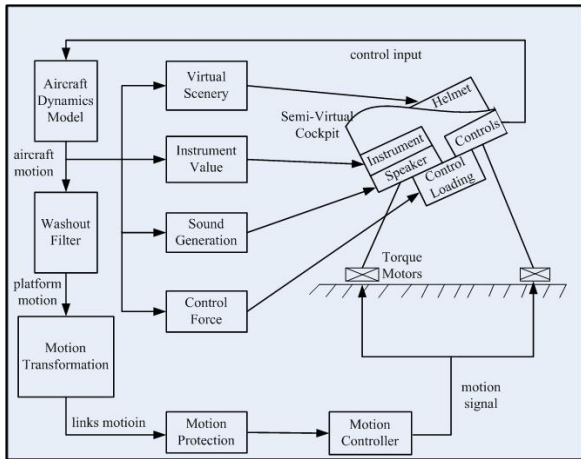International Journal of Computer and Systems Engineering
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Fig. 2 The architecture of the novel flight simulator

III. AIRCRAFT DYNAMICS MATHEMATICAL MODEL

An important component of the simulator's software is the aircraft dynamics mathematical model, which can calculate the aircraft's response to control inputs at various speeds and orientations. Then the output signal is transmitted to other subsystems to generate visual scenery, sound, motion and force feedback feeling for trainees. The aircraft dynamics model involves the principles of mathematical modeling of the aerodynamic, flight control, propulsion, ground handling and environmental characteristics of the aircraft [6]. The simulation of a complete mission, however, from take-off to landing, needs the nonlinear equations of motion, covering the full flight envelope.

The design and development of a full flight dynamics engine needs a flight test or purchasing a data package, which is temporarily unavailable for us. Therefore it is of critical importance to select an existing set of products which would provides the features we want. Several viable candidates including JSBSim[7], LaRCSim, X-Plane and Microsoft Flight Simulator are considered. Finally we choose JSBSim as our flight dynamics engine for the following three reasons: (1) it is an open-source software, which can lower the overall cost of the flight simulator; (2) it is highly configurable and can be easily reconfigured by a XML configure file as a different aircraft type; (3) it can be modified to meet our specific demand and can be added some special effects such as turbulences, for the reason that the whole source code is totally open.

IV. MOTION SYSTEM

As an important element of a flight simulator, the motion system serves to simulate the motion of aircraft and provide the pilot with realistic vestibular feelings and a part of tactile feelings. According to the FAA regulations, any device called "flight simulator" must have at least one motion system, otherwise it can only be termed a "flight training device" [8].

From fig.2, we can see that motion system consists of motion platform, electrical actuation module, motion transformation algorithm, motion controller, washout filter and motion

protection module. From the point of pilot, motion simulation can be regarded as a close-loop process. The pilot can feel the status of aircraft by platform motion and force feedback by control loading system, thus provides corresponding control command input. Then the aircraft dynamics mathematical model can compute reference motion of aircraft according to varying control input. Due to the limit workspace of motion platform, the reference motion can not drive the motion platform directly. It needs an intermediate algorithm called "washout filter" [9] to transform the aircraft reference motion signal to the platform reference motion signal. The washout filter divides the aircraft motion signal into two parts by making use of the characteristics of human vestibular feeling. One part, which is on high frequency domain, can drive platform directly and provide transient motion feeling for pilot. The other part on low frequency domain needs to be simulated by so-called platform-tilt technique, which makes use of gravity component to simulate the continuous acceleration and generates platform reference motion signal. Next a motion transform algorithm needs to be applied to transform platform reference motion signal from operational space to joint space. The motion protection module is then in operation to limit and damp the excessive reference link motion. And then the motion controller is responsible for tracking the reference link motion signal via real-time feedback control. Finally control signal is sent to electrical actuation module – six high-power torque motors to drive the whole motion platform.

Fig. 3 The low-profile motion platform with subsided cabin

The motion platform in flight simulator is often constituted of parallel mechanisms due to the requirements of bearing heavy loads and performing flexible movements. Among parallel platforms, six-DOF Stewart platforms gain most popularity in medium- and light-load situations. The traditional design solution of motion platform is to put all devices and cockpit into a cabin, and then the cabin is placed above the movable platform. This kind of design scheme has simple structure and is adopted by most of flight simulator. But the shortcoming of this scheme is also obvious. The whole simulator system is very high and it needs a dedicated three storeys high building to place. The safety problem also needs to pay more attention for such big equipment. Considering the

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above reasons, we design a low-profile motion platform (fig.3), which puts the cockpit below the movable platform. This scheme lowers the height of the whole system and the simulator can be disposed in the common office buildings and is safer to operate due to its lower gravity center. Although there are so many advantages, the special design scheme may also cause some problems such as workspace shrinkage of motion platform, which will affect the design of washout filter and motion protection module.
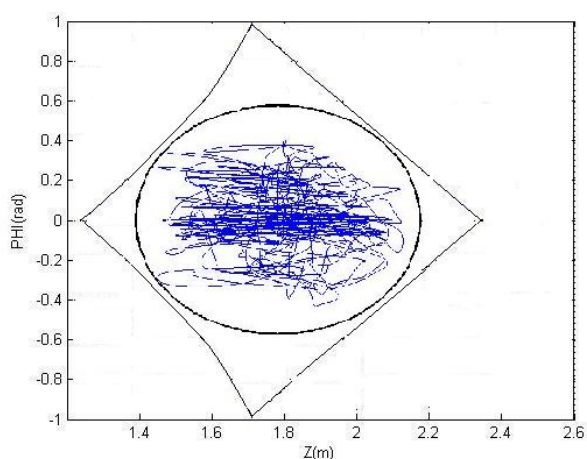

Fig.4 Required workspace must locate in the scope of reachable workspace

The parameters of washout filter have to be matched with dynamical performance and workspace of the motion platform. Otherwise, the motion reference signal output from washout filter may exceed the reachable space and make the movable parts reach the physical limit, and thus cause the interruption of simulation process. So first we compute the reachable workspace according to kinematic parameters and structure of motion platform. And then we compute the required workspace, which is determined by both aircraft dynamics mathematical model and washout filter. The design demand of motion platform is that the required workspace must locate in the scope of reachable workspace (fig.4). Because the mathematical model will not change as soon as we determine the aircraft type, the required workspace is only related to parameters of the washout filter. Several classical maneuver tasks are chosen for getting the required platform motion envelope. Through iterative optimizations, finally we get the optimized washout filter which can maximally exploit potentialities of the low-profile motion platform.

As to motion protection module, the traditional Stewart platform only needs to consider the length limit of links. The interference problem of links can always be avoided through elaborate structure design. But for our low-profile motion platform, interference between subsided cabin and links is a serious problem to be considered. We developed a virtual spring algorithm which exerts a virtual spring force to subsided cabin if cabin and links is getting too close.

V. SEMI-VIRTUAL COCKPIT SYSTEM

The biggest difference between our novel flight simulator and traditional flight simulator is the design philosophy of cockpit system. The cockpit of traditional flight simulator is almost a replication of true cockpit and generally has a wide-view projection system to generate high quality virtual out-of-window scenery. This kind of cockpit system has high fidelity and trainees do not have to wear any accessories during training. But the wide-view projection system is expensive and huge. And the simulated cockpit also needs a lot of money to build and can only be corresponding to one kind of aircraft.

In some of the military flight simulators, there is another cockpit system called "virtual cockpit" [8]. Virtual reality (VR) technology simplifies the design of the whole cockpit system and visual system. Helmet monitor is adopted to provide both out-of-window and inner cockpit scenery including appearance of all instruments. Data glove and position tracker are used to track the hand motion and then computer generated 3D hand model can be provided as visual indication for trainees. Virtual cockpit is flexible enough and can be easily reconfigured to a different aircraft type. And its building cost is significantly reduced for the reason that many functions can be realized by sophisticated designed software instead of expensive hardware. But due to the cumbersome of data glove, the trainees may feel uncomfortable to operate instruments in cockpit. That will reduce the immersion feeling of trainees.

Fig. 5 The inner cockpit and out-of-window virtual scenery

To overcome above shortcomings, we improve the design of virtual cockpit with mixed reality technology. Two cameras, mounted on the helmet near the trainee's eyes, are used to capture the images of hand manipulation. Then the hand images, extracted with skin color cue, are merged into the virtual scenery which is displayed on the helmet's monitors. This kind of design scheme does not need data gloves any longer and can eliminate the uncomfortable and intrusive feeling. Trainees can see their real hands and manipulate instruments freely. Due to its feather of merging real-world hand and virtual scenery, we call this scheme semi-virtual cockpit against virtual cockpit concept with totally virtual hand and scenery. It perfectly combines realistic feeling of traditional cockpit and low-cost design philosophy of virtual cockpit.

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VI. Control Loading System

When the pilot initiates a control input in a real aircraft, the aircraft's control structures always provide a counterforce as the control mechanics carry out that input. A flight simulator requires responding to pilot control inputs in a manner closely comparable to the aircraft being simulated. Control loading system is this kind of subsystem fulfilling the task. It recreates the control feedback loop necessary for the simulation of primary flight controls such as the yoke and rudders.

In traditional flight simulator, hydraulic control systems are utilized to produce proper forces on pilot control systems [10]. But hydraulic systems may be encounter system failures such as hydraulic leaks. And its building and maintenance cost is relatively high. So in our low-cost flight simulator, an electrical driven control loading system is designed to provide counter forces to pilot control inputs. The control loading is simulated by servo motor systems. Position sensors, used to detect displacement of the controls, are needed because the effect of control displacement differs depending upon the airspeed of the aircraft. And force sensors, used to measure actual force that servo systems exert, provide force errors feedback between reference control forces and actual forces. Servo motors are responsible for tracking reference control forces which should feedback to pilots. Then the force tracking process is closed-loop controlled by computer. The whole electrical driven control loading system has much lower cost and more flexibility than the traditional hydraulic system.

Fig. 6 Real cockpit with control loading system

VII. Other Subsystems

Other subsystems including acoustic system, communication system and control console.

The acoustic system includes sound database module, sound generation module and sound display module. The sound database module has all the sources of engine sounds, tire sounds, wind noise and other background sounds. The sound generation module is realized with an open-source 3D sound library and synchronized with visual scenery.

The communication system connects all the other subsystems with UDP protocol and manages the frame rate of the whole system. The core frame rate, dominated by aircraft

dynamics mathematical model, is 60Hz. Consider the characteristics of human vision, the simulator's visual system is downsampled to 30Hz. The motion system needs to stabilize the whole control system, so it runs on a real-time OS layer with a high frame rate of 1KHz. The frame rate of other systems is same as the core frame rate.

The control console controls the whole simulation process including initializing subsystems, system startup and run-time management. Another function of the control console is to provide visual indication of simulator's status. Fig.7 is a screenshot of the control console software.
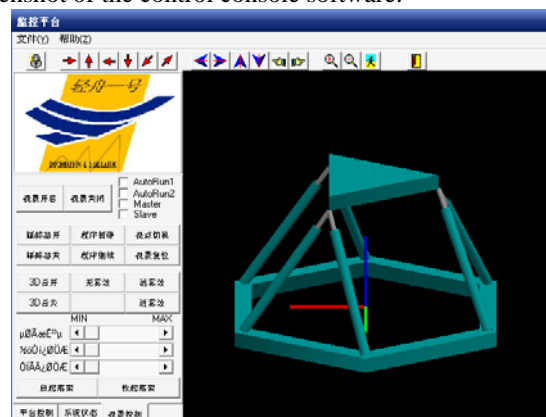

Fig. 7 Screenshot of the control console's GUI

VIII. Conclusion

A novel flight simulator with the development goals cost effectiveness and high performance has been realized. It shows its advantages over traditional flight simulator by its features achieved with open architecture, software solutions and low-cost hardware. Starting from general architecture of this complex equipment, all the various subsystem have been analyzed and described, with particular emphasis on the new technologies and novel design solutions which aim to reduce the complexity and cost of the whole system.

References

[1] L. Thomas, B. Edward and B. C. Judith, "Initiative towards more affordable flight simulators for U.S. commuter airline training," Proc. Royal Aeronautical Society Conf. on Training, Lowering the Cost, Maintaining the Fidelity, 1996, pp. 2.1-2.17.

[2] F. Holzapfel, I. Sturhan and G. Sachs, "Pilot-in-the-loop flight simulation – a low-cost approach, " AIAA Modeling and Simulation Technologies Conference and Exhibit, 2004.

[3] R. S. Burns, M. M. Duquette, J. B. Howerton and R. J. Simko, "Develop of a low-cost simulator for demonstration and engineer training, " AIAA Modeling and Simulation Technologies Conference and Exhibit, 2003.

[4] N. D. Macchiarella, T. Brady and P. K. Arban, "High fidelity flight training devices in the training of ab initio flight strudents, " IEEE Digital Avionics Systems Conference, 2005.

[5] H. Tamura, H. Yamamoto and A. Katayama, "Mixed reality: future dreams seen at the border between real and virtual worlds, " IEEE Computer Graphics and Applications, 2001, pp.64-70.

[6] M. Baarspul, "A review of flight simulation techniques," Prog. Aerospace Sci., vol.27, pp.1-120, 1990.

[7] J. Berndt, "JSBSim: an open source flight dynamics model in C++, " AIAA Modeling and Simulation Technologies Conference and Exhibit, 2004.

[8]   B. C. Judith, N. S. Nancy and L. Thomas, "Simulator platform motion -
      the need revisited," The International Journal of Aviation Psychology, vol.
      8, no. 3, pp. 293–317, 1998.
[9]   M. A. Nahon and L. D. Reid, "Simulator motion-drive algorithms – a
      designer's perspective," Journal of Guidance, Control and Dynamics, vol.
      13, no. 2, pp.356-362, 1990.
[10] J. M. Rolfe and K. J. Staples, Flight Simulation. Cambridge University
      Press, 1988.