Design of a Virtual Borescope: A Presence Study

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Abstract

Increased emphasis on aircraft inspection to ensure aviation safety has resulted in the need for a better trained workforce of aircraft maintenance personnel. As almost 90% of inspection is visual in nature, it has led to the development of computer simulators to train human inspectors performing the inspection task. However, the lack of immersion and interaction has led to limited effectiveness in such simulators. This paper details the first phase of the development of a virtual borescope. Using a simple model of the turbine and stator of a Pratt and Whitney PT6 engine, the simulator was evaluated using a modified version of the Witmer-Singer Presence Questionnaire (PQ). Based on the responses of the expert participants, it was observed that the realism and interaction of the simulator was comparable to that of the actual borescope. Although the participants commented on the lack of constraints while interacting with the simulator, they experienced a high degree of correlation between the actions performed in the virtual simulator and the actual borescope inspection.

1 INTRODUCTION

Visual inspection comprises a major proportion of the aircraft maintenance procedure [3, 4]. This is usually preformed by an aircraft maintenance technician, who is trained in the inspection procedures, identification and classification of defects. Most of the theoretical knowledge on the inspection procedures is gained from classroom teaching. On-the-job training by a more experienced inspector is used to bridge the gap from the academic setting to a more practical workplace environment. However, this transition from the classroom to the workplace is not easy. Many novice inspectors face a steep learning curve because they lack the required hands-on experience required to make a smooth transition to the workplace.

The major limitation in providing more practical experience to the students is the prohibitive costs associated with obtaining different types of aircraft to train the students. Computer-based training simulators have been used for enhancing the skill set of the novice inspectors [5, 10]. Due to advances in the commodity graphics market and the availability of faster and cheaper Graphics Processing Units (GPUs), the visual realism of the simulators has improved considerably. The training simulators vary in realism and degree of interaction, from a simple desktop point-and-click version to a fully immersive, virtual reality simulator [13]. In controlled settings, it was observed that participants who had prior training with simulators performed better than those who did not [5]. Although these simulators facilitate cost-effective, hands-on training in the classroom, it is to be noted that they are meant to merely augment, not replace, on-the-job training.

As a part of using technology to improve aviation safety, previous research at Clemson University has investigated the benefits of incorporating virtual reality simulators to train novice inspectors on visual inspection in wide-bodied aircraft. Presence studies used to evaluate the simulator found a high degree of correlation with the real world [10, 15]. In continuation with these efforts, this project aims to develop a virtual borescope for training students in aircraft engine inspection. Consistent with the iterative design and evaluation methodology, this paper presents the results of the presence study conducted to evaluate the visual aspects of the first phase of the simulator.

This paper is organized as follows: Section 2 provides a brief description of the borescope and its use in the aircraft maintenance industry together with the previous research involving virtual simulators for training. Section 3 details the methodology and the procedures adopted while evaluating the virtual simulator. Section 4 presents the results of the presence study, while Section 5 provides a brief discussion of the results. We conclude in Section 6 with a summary and description of the future work.

2 BACKGROUND

Virtual simulators have been used for training novices in a wide spectrum of areas, ranging from flight training to surgical simulators [2, 6, 7, 8, 11, 16, 17]. The simulator usually consists of a 3D model rendered on the computer with which the users can interact in real-time using input devices ranging from a simple joystick to a more expensive 6 degree-of-freedom (DOF) mouse. The displays vary from a simple computer monitor to fully immersive head-mounted-displays. In this paper, we consider mainly non-immersive training simulators.

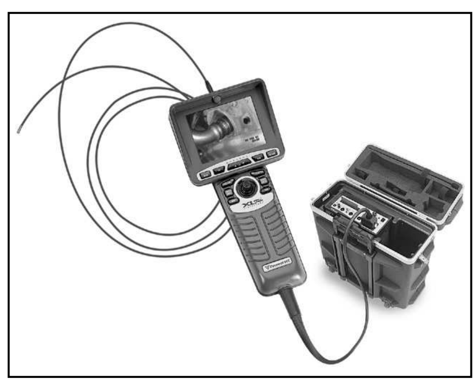
This section is organized as follows: Section 2.1 describes the borescope and its application in the aircraft maintenance procedures. Section 2.2 describes some of the previous endeavours undertaken to develop virtual training tools similar to the borescope and we conclude in Section 2.3 with an outline of the iterative design process adopted for the development of the virtual simulator.

2.1 Borescope

The borescope is a tool used to inspect the internal parts of the engine for defects such as cracks, stress fractures and corrosion. The most commonly used form of the borescope is the video borescope. Although other forms of the borescope such as the optical borescope, pictured in Figure 1(a), are in use, the video borescope is more advanced and has numerous advantages over the optical borescopes. In this paper, the term borescope is taken to refer to the video borescope.

The borescope consists of a handheld unit and a long, flexible, fibre-optic cable as shown in Figure 1(b). The handheld unit consists of a full color LCD screen and a mini-joystick. The fibre-optic cable is connected to the tip of the handheld unit and has a camera and light source at the other end. The joystick controls the articulation of the fibre- optic tip attached to the unit. Buttons on the handheld enable the inspector to take screen captures of the images on the LCD screen or return the articulating tip to the neutral position before withdrawing the fibre-optic cable from the engine. The inspector can also obtain a closer view of the engine components by using the magnification button on the handheld device.

To perform a borescope inspection of the engine, the inspector first inserts the fibre-optic cable through the fuel injection manifolds on the engine casing. Usually, a special guide tube is used to steer the tip of the borescope through the various stages of the turbines and stators and directly to the hot-section of the engine. The borescope is then manipulated with the help of the joystick and the turbine blades are inspected for defects. The borescope inspection can either be performed by a single inspector who guides the borescope tip through the engine, or by two persons. In the latter case, the technician performing the inspection keeps the borescope stationary in a fixed position in which he has full view of the turbine, while the other person manually rotates the engine shaft, which in turn rotates the turbines. Although this solution is viable in case of small engines, it is not practical in case of wide-bodied aircraft.



a) Optical borescope b) Video borescope (Courtesy Everest VIT)

Figure 1: Optical borescope (left) compared to the video borescope (right)

2.2 Past Research

The borescope is similar in design to the commonly used medical tools such as the endoscope. Both instruments are used to check for abnormalities by visual inspection. The skills and the hand-eye coordination needed to manipulate the articulating tip in both these devices are similar in nature. However, there are two major differences between the instruments. Whereas the endoscope displays the view as seen from the camera on a TV screen, the borescope provides the output of the camera on a 3" x 2" LCD panel on the handheld device. The second and more important difference is that, unlike the borescope, tissue deformation occurs due to the contact between the walls of the intestine and the endoscope as it is traversing through the human body cavity. For a realistic representation, this has to be taken into consideration while designing the virtual endoscopy simulator.

Past research has led to the development of "desktop VR" simulators for training doctors in bronchoscopy, colonoscopy, etc [2, 6, 14, 15]. Virtual endoscopy consists of navigation of a virtual camera through a 3D reconstruction of a patient's anatomy enabling the exploration of the internal structures to assist in surgical planning. Virtual exploration through patient-specific data can help the surgeon perform a diagnosis without having to operate on the patient. The data can also be used to train novice doctors in the correct procedures to be adopted for performing the operation. Virtual endoscopy can be used to screen, diagnose, evaluate and assist determination of surgical approach, and provide surveillance of certain malignancies [17].

The basic methodologies adopted in developing the various virtual endoscopy medical training simulators for are similar. As the first step, high resolution data obtained from CT scans or MRI are used to reconstruct realistic, 3D models of the human anatomy. If needed, the operator can configure the 3D data with texture-mapping to introduce abnormalities such as tumours, lesions and polyps to the 3D models. Physically realistic effects such as soft tissue deformation and haptics can also be used to increase the sense of realism and presence in the simulator. Evaluation studies used to assess the realism of such simulators showed that participants felt that the virtual simulators strongly represented the real world environment [5, 17]. The second and most important step is the user interaction in the virtual model. The participants can either use a "free-fly" model of camera or use a predetermined route to navigate through the model. Using a variety of input devices, the users interact with the virtual scene and perform pre-defined tasks which help determine the effectiveness of the simulator. The third step consists of assessing the benefits of training with the virtual simulator in the real world scenario. Process and performance measures such as the total time taken, tumours identified and missed as well as subjective questionnaires are used to evaluate the simulator.

Ferlitsch et.al. observed that novices trained on such simulators performed their tasks faster and with fewer errors than those who did not have similar training [5]. They also observed that there are distinct differences between the strategies adopted by expert doctors and novices when they were asked to use the simulator. It was also found that using real life props, such as a mannequin, and providing real time force feedback increased sense of presence and realism of the virtual simulator [7, 8, 17]. Although repeated training on the simulators have been found to improve the performance of novices, the transfer effects of training on virtual simulators and performance in the real world have not been fully studied. We plan to investigate this aspect of training simulators by developing and evaluating the virtual borescope.

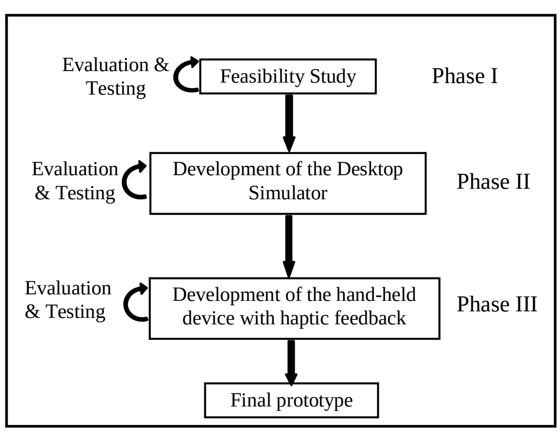


Figure 2: Iterative design methodology with user evaluation at each step

2.3 Iterative Design Methodology

The virtual borescope project seeks to develop a realistic representation of the borescope inspection process for training students in adopting correct procedures for aircraft engine inspection. The project has been divided into three iterative phases as seen from Figure 2. The first phase is a pilot study where the feasibility of developing the virtual borescope is analyzed with the help of a pilot simulator. This paper describes the expert inspectors' evaluation of the first phase of the simulator. The second phase will lead to the development of a desktop version of the virtual simulator with realistic textures for defects and user performance metrics used to evaluate the simulator. The third phase will result in the development of a hand-held device similar to the actual borescope, but with the 3D models on the LCD screen and haptic feedback for a realistic, training experience.

3 PROCEDURE

3.1 Equipment

The experiment was carried out on a Pentium 4, 2.6 GHz computer, with 512 MB of RAM and a GeForce 5700Ultra graphics card. The frame rates were maintained above 30fps for an interactive, real-time experience. An off-the-shelf Gravis Eliminator Pro gamepad was used control the camera position and orientation in the simulation. Unlike the actual borescope where the tip has limited motion, the camera in the virtual borescope had no constraints and could rotate a full 360° about either axis. The camera orientation was controlled by the analog, 2-axis directional pad on the gamepad. Two buttons on the gamepad simulated the feed and withdrawal of the probe by moving the camera along the direction of the view vector. The experimental setup is shown in Figure 3(a), with a close-up view of the gamepad in Figure 3(b).

3.2 Subjects

Eight participants (all male) were invited to evaluate the virtual borescope. All the participants were familiar with the video borescope and had extensive experience using the borescope for aircraft engine inspection. Each of the participants was either an aircraft maintenance technician or taught an aircraft maintenance course on engine and aircraft inspection. The participants were asked to interact with the desktop version of the borescope simulator and express their observations on the visual realism and correctness of the simulator. Their comments were recorded for later transcription. On completion of the experiment, the participants filled out presence questionnaire that evaluated the visual fidelity of the simulator.

3.3 Methodology

Before the development of the simulator, a detailed task analysis of the borescope inspection was carried out at Steven's Aviation and the Aircraft Maintenance School at Greenville Tech [12]. An expert inspector was video taped performing a mock engine inspection and his comments and observations recorded for later transcription.

Figure 3: The experimental setup (a) with a close-up of the gamepad (b)

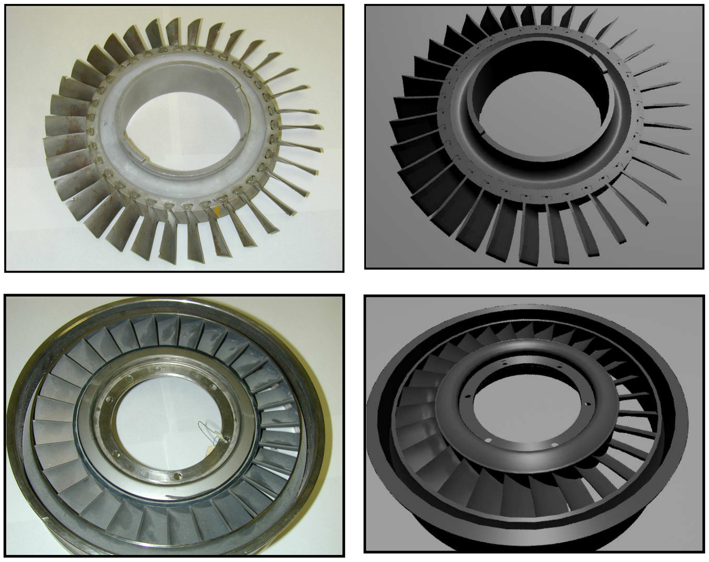


Figure 4: Actual engine blades (left) with modeled blades (right)

Using the hot section of a Pratt and Whitney PT6 engine, 3D models of the turbine and stator was modelled using Alias Wavefront's Maya [1]. The 3D models of the engine blades along with the real blades are shown in Figure 4.

The 3D models of the engine blades were combined together and enclosed in a simple sphere to simulate the experience of performing the inspection on an actual engine. This combined engine was imported and rendered using OpenSceneGraph [9]. Collision detection was enabled in the simulator to prevent the participants from moving the camera directly through the engine blades. Depending on the angle of incidence at the collision point, the camera either slid along the surface of the engine or it stopped without any further motion, until the participant changed the position or the orientation of the camera. Unlike actual engine, the 3D model was "pristine", i.e. there were no defects on the engine blades such as cracks and corrosion. The main aim of the experiment was to determine the perceived sense of presence and realism experienced by the participants using the virtual simulator.

1. The environment was responsive to actions that I initiated.
2. The interactions with the environment seemed natural.
3. I was involved by the visual aspects of the environment.
4. The mechanism which controlled movement through the environment seemed natural.
5. The visual aspects of the virtual environment seemed consistent with my real-world experiences.
6. I was able to anticipate what would happen next in response to the actions that I performed.
7. I could examine objects from multiple viewpoints.
8. Manipulating the borescope tip in the virtual environment seemed compelling.
9. I was involved in the simulated borescope experience.
10. The control mechanism was distracting.
11. There was no delay between my actions and expected outcomes.
12. I adjusted quickly to the virtual environment experience.
13. I felt proficient in moving and interacting with the virtual environment at the end of the experience.
14. The visual display quality interfered with performing the task.
15. The control devices interfered with performing the task.
16. I could concentrate on the task rather than on the mechanisms used to perform the task.
17. The software is applicable for training borescope inspection of engines.
18. I would personally prefer the environment for training of borescope inspection.

Table 1: Modified version of the Witmer-Singer Presence Questionnaire for evaluating the simulator

Before the experiment, the participants were asked to complete a demographic questionnaire which collected data related to their familiarity with the borescope and engine inspection procedures. The participants were then presented with the virtual borescope simulator. The authors demonstrated the use of the gamepad to control the camera motion in the simulator. The participants were then asked to use the gamepad and navigate through the 3D models. The participants were given unlimited time to interact with the simulator. They were instructed to "think aloud" during their interactions with the simulator and comment on the visual fidelity and interaction experience in the simulator. Their observations and comments were recorded for later evaluation. Once they completed the experiment, the participants were asked to fill out a modified version of the Witmer-Singer Presence Questionnaire, which evaluated the realism of the simulator on a seven-point Likert scale, ranging from strongly disagree to strongly agree, with four (4) being neutral. The questionnaire is shown in Table 1.

4 RESULTS

The results were analyzed using SAS (v8.2). The Wilcoxon test was used to examine the significance of the deviation from the neutral point 4 on the Likert scale. The results are summarized in Table 2.

Question	Mean	Std Deviation	Significance of the deviation from neutral value 4* Wilcoxon test P value
1	6.125	0.640	**0.0078****
2	6.0	0.534	**0.0078****
3	5.75	1.164	**0.0313****
4	6.0	0.755	**0.0078****
5	5.75	1.388	0.0703
6	6.25	1.035	**0.0156****
7	6.25	1.388	0.0703
8	5.75	1.488	0.1250
9	6.125	1.356	0.0703
10	2.0	0.534	**0.0078****
11	6.0	0.925	**0.0156****
12	6.125	1.125	**0.0156****
13	6.375	1.060	**0.0156****
14	3.375	2.133	0.4531
15	2.125	0.991	**0.0156****
16	5.875	0.991	**0.0156****
17	6.25	0.707	**0.0078****
18	5.875	1.246	**0.0313****

* Based on a seven point Likert scale where 1 was strongly disagree, 7 was strongly agree, and 4 was neutral
** Significant

Table 2: Results of the Wilcoxon Test

The results show a significant inclination ($p < 0.05$) of the participants to agree to questions 1, 2, 3, 4, 6, 11, 12, 13, 16, 17 and 18 to disagree with questions 10 and 15. There was no significant deviation from the neutral value for the responses to questions 5, 7, 8, 9 and 14.

5 DISCUSSION

The analyses of the results allow us to evaluate the degree of presence of the borescope simulator. There were no significant responses against the simulator. The participants found the environment to be responsive and felt involved in its visual aspects. The participants experienced no delay in the simulator's response and were able to anticipate the responses to their actions. The participants adjusted quickly to the virtual experience and could concentrate on the task without being distracted by the control mechanism involved. They found the interactions with the environment to be natural. All these results signify a high degree of presence experienced by the participants in using the simulator.

The prototype of the virtual borescope which was used for this study had a pristine (free of any defect/ blemish) model of the engine components. This was pointed out to us by the participants. This is also evident from their neutral response to question 5 which evaluated the consistency of the virtual environment with the real world. The prototype also used a standard gamepad for interaction with the simulator. The responses to questions 2, 4, 10, 13, 15 and 16 indicate that the interactions with the virtual simulator using the gamepad interface did not distract the participants or hamper them from feeling a high degree of presence in the environment. The participants did observe that the camera was unconstrained and pointed out that the articulating tip of the actual borescope probe was limited in its ability to move very freely within the engine. Responses to questions 17 and 18 indicate that the participants consider the virtual simulator to be a useful tool for providing training in engine inspection using borescopes.

6 CONCLUSIONS AND FUTURE WORK

This study evaluated the pilot prototype of the virtual video borescope. The results of the presence study indicate that the participants experienced a high degree of presence in the virtual model. The use of the gamepad and a desktop computer, instead of the joystick and the hand-held device, did not adversely affect the interaction in the virtual world. The participants were able to adjust to the virtual borescope and were adept at using it by the end of the task. The participants felt that the virtual borescope would prove to be a useful medium of instruction in the classroom for providing training in engine inspection procedures.

There were a few comments that the participants felt would address shortcomings in the pilot prototype. We plan to incorporate these suggestions in the next phase of the simulator. Most of the participants commented on the lack of defects and blemishes in the engine models. We plan to address this by using images of actual defects obtained from the video borescope and texture mapping them to the engine models. We are also in the process of developing an enhanced version of the camera to address the lack of constraints in the camera model. This model will have collision detection with multiple points along a curve to better simulate the fibre-optic probe of the real video borescope. In the future, we will be evaluating the transfer effects of the simulator with novice participants.

Acknowledgement and Disclaimer

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