Study on the Astronaut Error Criteria of a Manually Controlled Rendezvous and Docking Operation

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Abstract. *Objective:* In this paper, some manual control rendezvous and docking operations were researched, astronaut manual rendezvous and docking cognitive decision-making process and its operational characteristics were analyzed, and then the manual rendezvous and docking operations mistakes criteria was determined. *Method and Result:* By capturing operation errors during the operations, it can be easy to find weak points in astronaut's training to provide future reference *Conclusion:* It can accumulate the basis data for further process optimization rendezvous and docking procedure evaluation methods.

Keywords: Manual rendezvous and docking · Operator errors · Criterion · Training

1 Introduction

Manually controlled rendezvous and docking refers to the operation in which an astronaut observes the relative positions and attitudes of two space vehicles through shipborne equipment such as a television camera on the tracing space vehicle, and then operates the manual controller to perform rendezvous and docking [1]. Manually controlled and automatic rendezvous and docking technology serve as backup for each other [2]. In the man–machine interface system that comprises the astronaut and the spacecraft, the astronaut handles control operations while performing the manually controlled rendezvous and docking operation. In these operations, certain errors are unavoidable. These operational errors are anthropogenic as they result from human error [3].

Human factors analysis and classification system is a qualitative method employed in research on human errors. Specific and targeted human error corrections and preventive measures can be determined through retrospective classification analysis. The classification of human errors may be applied in many fields including spaceflight, nuclear power, transport, and other technically complicated areas [4–7]. Human error classification research has already been performed abroad. Several human error classification systems have been proposed, for example, Norman [8] proposed promulgating

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the seven-stage action theory of human behavior in man–machine interactions, Reason [9, 10] proposed human apparent error and human hidden intention error classification models, and Rasmussen [11, 12] proposed the error classification method of knowledge-based, rule-governed, skill-oriented, cognitive behavior models, among other classical classification theories.

Currently, operational errors in manually controlled rendezvous and docking performed by astronauts are not clearly defined. In this paper, the evaluation criteria mainly pertained to handling operational errors based on the abovementioned human error classification models and the practical training experience of the astronaut. By analyzing manual control rendezvous and docking operations, operational errors were classified as relative spatial relationship perception errors, control decision errors, and handle operation execution errors based on cognitive psychology. As these operational errors will increase the number of repetitions of an operation in the entire manually controlled rendezvous and docking process, it can result in increased fuel consumption. Meanwhile, the in-flight stability of the spacecraft will also be affected and the failure rate of the docking mission will increase. It is of vital importance to determine a method to recognize operational errors in the training process more accurately and increase the operational accuracy rate of astronauts during training for manually controlled rendezvous and docking missions. By laying down criteria to capture error classifications effectively, this paper provides support for cognition, decision process, and the design of corresponding software for capturing operational errors made by astronauts.

2 Operational Definition

Astronauts accomplish rendezvous and docking of two spacecraft through several operations using the control handle. Each operation includes the processes of perception, which pertain to the perceived relative spatial orientation of the two spacecraft, decisions relating to handle control, and implementation of actual operational behavior. The determination of relative spatial orientation provides the basis for control handle decisions necessary for further control and implementation of the corresponding handle operation. The result of each operation will serve as feedback to provide new status information for determining the subsequent spatial positioning of the spacecraft.

The procedures for image perception, control decision, and operational implementation are conducted continuously and consecutively in the manually controlled rendezvous and docking mission until the docking process between the two spacecraft is complete. Thus, each control handle operation used for the control of the rendezvous and docking process in the astronaut's manual was studied to decide the corresponding operational error criterion.

The astronaut performs manually controlled rendezvous and docking by controlling the handle for translational motion and the attitude handle to complete the operation. Each time the astronaut controls the handle, a corresponding output voltage is generated. The thrust size and direction of the spacecraft propulsion system are determined based on the direction and size of the output voltage of the handle. Thus, the operational motion of the astronaut can be recognized by the change in output voltage of the handle during the docking process. Therefore, each operation was defined as the process from the start of operation of the control handle (for translation or attitude) to the end stage where production of voltage signal from the handle is reset to zero, which is the voltage signal at the initial position.

3 Handle Control Characteristic and Operation Analysis

The two handles in rendezvous and docking equipment have different control characteristics. Thus, the operation strategies are also slightly different. Therefore, it is necessary to perform classification analysis on the observed errors.

3.1 Translational Handle Control Process and Error Analysis

The translational handle has two handle heads, one of which can be propelled forward and backward to control the translational motion of the spacecraft in the forward and backward directions. The big-head handle can have translational motion along a single axis or both axes to separately or simultaneously control the translational motion of the spacecraft in the downward, left, or right directions.

During manually controlled rendezvous and docking, the translational handle can change the thrust direction. In addition, the size of the spacecraft influences its speed. When the translational handle returns to zero, the speed of the spacecraft is unchanged. When the acceleration returns to zero, the spacecraft maintains an approximately constant forward speed. This requires the astronaut to prejudge an appropriate opportunity to slow down or speed up to maintain the spacecraft in an appropriate position [10].

The translational position reflects the relative position and distance between two spacecraft. The astronaut estimates the relative position information between two spacecraft using the image information. Later, the astronaut controls the handle to make the engines of the spacecraft to produce higher speeds. At a remote distance, positional deviation can be estimated using information such as the lateral visible area of the target spacecraft. At a close range, the astronaut can estimate the positional deviation by using the distance between the scribed line on the upper chassis and the center of the cross target. In actual operation, the astronaut may incorrectly perceive the current image information, incorrectly estimate the spatial position relationship, fail to consider the relationship between current position and speed during decision-making, or commit control operation errors, all of which can cause the spacecraft to travel beyond the preset position with increasing deviation in translational position. Thus, errors relating to the translational handle operation were regarded as rendezvous and docking operation errors.

3.2 Attitude Handle Control Characteristics and Process Analysis

The attitude handle has three axes of rotation. It can rotate around a single axis, around two axes at the same time, or around all three axes to control the roll, pitch, and off-course attitude.

The attitude relationship reflects the relative attitude angle between two spacecraft, including those for off-course, pitch, and roll. The attitude of the maneuvering spacecraft should be consistent with the attitude of the target spacecraft to complete rendezvous and docking successfully. Therefore, the astronaut must adjust the flight attitude of the spacecraft during the rendezvous and docking process. With regard to the judgment of attitude, the astronaut needs to reconstruct the spatial relationship between the two spacecraft based on the spatial image, which requires imagining the three-dimensional relative attitude relationship using the two-dimensional frame information. Thus, the attitude relationship of the spacecraft must rely on accurate imagination and judgment regarding three-dimensional space of the two spacecraft to allow correct adjustments. During the actual operation, it is easy to err in perceiving current image information, misjudge the attitude direction relationship, operate the wrong handle when making decisions, or perform an incorrect operation while controlling the handle; these errors result in a large deviation in spacecraft attitude direction and high fuel consumption, which prevent successful docking. Therefore, attitude handle operation errors were regarded as rendezvous and docking operation errors in this paper.

3.3 Field Switching Control Characteristics and Process Analysis

The astronaut observes the target spacecraft mainly through the image information captured by wide field and narrow field cameras during the process of rendezvous and docking. The field angle of the wide field camera is large, which makes it convenient for the astronaut to observe the target spacecraft from a longer range and acquire comprehensive information of the docking channel. The field angle of the narrow field camera is small, which makes it convenient for the astronaut to observe the aim-point and other information regarding the target spacecraft clearly to accomplish rendezvous and docking accurately. In an actual docking operation, when the maneuvering spacecraft is at a remote distance, the astronaut can switch to the narrow field camera to acquire detailed image information at the time when the target spacecraft appears at the center of the display screen that displays the frame captured by the wide field camera. In engineering design, the position of the wide field camera can deviate from the target position of the spacecraft. Over-reliance on the wide field camera can present a risk of failure during docking.

4 Design of Operational Error Criteria

Based on the above-mentioned analysis, manual control rendezvous and docking operation errors were divided into three categories: translational handle operation errors, attitude handle operation errors, and field switching operation errors.

4.1 Operational Error Criteria for Translational Handle

With the objective of determining the translational handle control characteristics, translational handle operation errors were considered to exist under the following four conditions:

Error in Control Direction. The operator makes a control action in the opposite direction, which results in increased deviation between the spacecraft and the target location. For example, when the spacecraft is moving leftward at a certain speed and the operator moves the handle towards the left to make the spacecraft accelerate further leftward, it can result in the spacecraft deviating from the target spacecraft at a higher speed.

Insufficient Degree of Operation. The current speed of the spacecraft and relative deviation between it and the target spacecraft are misjudged resulting in a low degree of control. For example, when the spacecraft is moving toward the target point and the astronaut operates the handle to slow down the spacecraft, an insufficient degree of control can cause the spacecraft to overshoot its intended target position.

This error can occur in two circumstances:

1. The perception of speed is wrong. For example, when the spacecraft is moving close to the target spacecraft and the braking mechanism is insufficiently applied, the spacecraft will not be able to slow down and stop at the target point.
2. The perception of position is wrong. For example, when the spacecraft is moving close to the target point, an insufficient deceleration due to miscalculation of position can cause the spacecraft to overshoot the target point.

Excessive Degree of Operation. The degree of control may be in excess if the operator misjudges the current speed of the spacecraft and the relative deviation between the targets. For example, when the spacecraft is moving towards the target point, the astronaut operates the handle to accelerate the spacecraft to get it closer to the target point. An excessive degree of operation causes the spacecraft to overshoot the target point.

The operator may also incorrectly perceive the position. For example, an excessive amount of control operation causes the spacecraft to overshoot the target point.

An incorrect perception of speed can also lead to an excessive amount of control operation. For example, when the spacecraft is too close to the target spacecraft and excessive acceleration is applied, the spacecraft will not be able to slow down sufficiently to stop at the target point.

Untimely or Omitted Operation. When speed of the spacecraft or relative deviation between the targets are misjudged, the control handle is not operated in time, the spacecraft comes close to the target spacecraft at a high speed, or direct deviation between the two spacecraft is small, the maneuvering spacecraft will overshoot the target spacecraft if there is a lack of timely manipulation of speed.

Operational Error Classification for Translational Handle

Error 1: direction operation error
Error 2: perception of speed was wrong, which resulted in excessive operation
Error 3: perception of position was wrong, which resulted in excessive operation
Error 4: perception of speed was wrong, which resulted in insufficient operation
Error 5: perception of position was wrong, which resulted in insufficient operation
Error 6: untimely or omitted operation

4.2 Operational Error Criteria for Attitude Handle

With the objective of determining the attitude handle control characteristics, attitude handle operation errors were considered to occur in the following two circumstances:

Control Direction Error. If the current relative attitude of the spacecraft is misjudged, it can result in wrong adjustments of direction when controlling the attitude handle. For example, when the spacecraft is in left drift, the astronaut may operate the handle in a wrong direction resulting in an increase in the angle of the left drift.

Excessive Control Operation. Because the relative attitude between two spacecraft is usually very small in actual manually controlled rendezvous and docking, the spacecraft will have an angular speed of forward and backward drift. The attitude of spacecraft can be changed by controlling the handle. Thus, accurate attitude operation is critical for operational quality. In this study, we focused on errors caused by the operator because of incorrect perception, incorrect decision, or incorrect operation. Therefore, we mainly aimed to capture the errors relating to the direction of attitude control. The control of the attitude angle was judged as an operational error only if the adjustment made to the attitude angle was no larger than the deviation of the initial adjustment.

Operational Error Classification for Attitude Handle

Error 1: error in direction of operation
Error 2: error in degree of operation

4.3 Field Switching Operational Error

According to the requirements mentioned in the manual control rendezvous and docking training, docking must be completed during the time when the narrow field camera is being used. For the convenience of implementing follow-up operations, it is required that the astronaut should stabilize the target aircraft to the center of the screen when there is a distance of 30 m between the two spacecraft. Therefore, 30 m was selected as the specified distance by which it is necessary to have switched to the narrow field camera. Not switching to the narrow field camera at X <= 30 m was defined as an operational error.

Field Switching Operational Error Classification

Error: narrow field switching was not conducted when X <= 30 m

5 Implementation of Operational Error Capture Software

Operational error capture software can identify incorrect operations made by astronauts during manually controlled rendezvous and docking. In addition, the perception and decision-making process of astronauts were analyzed using a complementary questionnaire. The system included two major modules: the data access module and the error treatment module.

The data access module is responsible for reading the initial data from the rendezvous and docking simulator and generating output data after the errors are corrected. According to the definition of the manually controlled rendezvous and docking operation, the operation begins from the absolute value of the voltage signal received by the manually controlled rendezvous and docking simulator, which is 0.5 V, and ends when the voltage signal returns to zero again. This is marked as a manually controlled rendezvous and docking operation unit of the astronaut. During the entire task execution process, the data access module extracted the operation units for error analysis from the simulator continuously. The output process consisted of error judgment, extraction of error operation by treatment module, error classification information, and generation of error questionnaire module. The error analysis for perception and decision making errors was output to an Excel file. For convenience of further data analysis, the output content includes operator ID, starting time of the task, total time, generated error operation number, relative flying speed of the spacecraft when an incorrect operation occurs, relative translational deviation, off-course attitude, direction of incorrect operation, and value of generated voltage.

The error treatment module is the essence of the software, which conducts error identification and classification according to the error judgment procedure performed on manually controlled rendezvous and docking operational data of astronauts. According to the operation units extracted by the data access module, the error judgment was conducted using a combination of error criteria and status information on the operation units obtained from the simulator. If it was determined that the operation units were in error, the error types were classified. In addition, the resulting information regarding error type, error quantity, and error rate (error quantity/total operation units) were transmitted to the data access module.

6 Software Testing

The operational error capture software had to be tested to verify its accuracy. In this study, primary instructors from the Chinese Astronaut Center were recruited to test various types of errors by designing specific test cases.

In the above-mentioned error criteria, the categorization of manually controlled rendezvous and docking operation errors and the defined error types included the procedures for translational handle, attitude handle, and field switching. There were nine types of errors in total. In the actual operation, the circumstances under which these nine types of errors occurred were recorded. These included the 9 error types corresponding to 37 error circumstances and 20 proper operational circumstances. When designing test cases, all 57 correct and error circumstances were taken into consideration. In this paper, 120 operational test cases were designed, which were aimed at the above-mentioned 57 operational circumstances. After testing all cases, the software met the criteria specified in the design requirement and judgment accuracy of the error software was 100%.

After the testing was concluded, it was replayed through a video. The accuracy and coverage of error identification were estimated by spaceflight experts. It was discussed and reviewed by astronauts and the engineering department. It was concluded that the design of the error capture software was satisfactory, which made the software capable of detecting operational errors in the manually controlled rendezvous and docking process for the benefit of the astronaut. The criteria used were reasonable but not excessively strict, which can be utilized for the detection of manually controlled rendezvous and docking operation errors.

7 Summary

In this study, the currently available classification models of human errors were reviewed. The operational characteristics of manually controlled rendezvous and docking process and the operational decision-making process of the astronauts were analyzed using cognitive psychology and based on manually controlled rendezvous and docking training given to astronauts. The same training guidelines were used to develop the criteria for rendezvous and docking operational errors, which were used for detecting errors in the perception stage, decision-making stage, and operational performance stage of the astronaut. Depending on the operational axis, operational errors were classified into translational handle control errors, attitude handle control errors, and field switching operational control errors. According to the cognitive process, the operational errors were classified into spatial perception errors, control decision-making errors, and handle operation errors. During their compilation, the error criteria were reviewed and tested by training instructors and astronauts. The accuracy of the error criteria was ensured by creating a detailed design and by modifying each error condition. This laid the foundation for further improvement of the error capture software. Additionally, this has provided a reference for evaluation of rendezvous and docking and improved the astronaut training process.

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