Helicopter tracking error and input aggression for point tracking tasks under boundary avoidance situations

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Abstract. Helicopters are broadly applied in complex and harsh task environment such as rescue mission and firefighting. These tasks require helicopters to operate in ground proximity, keep tracking the target while avoid obstacles to avoid trashing. The combination of point tracking and boundary avoidance tracking can be utilized to describe this task condition. This study implemented a simulation task on MATLAB and Simulink and utilized a simplified helicopter dynamic model to investigate point tracking and boundary avoidance tracking tasks. The analysis of variance (ANOVA) and regression analysis were used to analyze the effects of task conditions on participants' tracking error and input aggression. Results demonstrated that the overall tracking error had a negative correlation with input aggression, and that participants tended to have higher input aggression and lower tracking error near the boundary.

Introduction

During the process of creating and operating modern high performance rotorcraft, engineers and pilots must anticipate and manage unfavorable occurrences known as “Rotorcraft-Pilot Coupling” (RPCs)[1]. These phenomena emerge from the undesired and atypical coupling between the pilot and the rotorcraft and can lead to instabilities that are both oscillatory and non-oscillatory, reducing handling quality, increase structural strength requirements, and sometimes resulting in disastrous accidents.

Boundary-avoidance Tracking is a pilot-task model proposed by Gary[2], [3], which indicates that in the process of performing flight tasks, pilots not only need to complete the task of “maintaining specific parameters” (point tracking) but also typically need to “avoid certain parameters” (boundary avoidance. Researchers believe that boundary avoidance behavior has a strong correlation with the critical phenomenon of PIO, which previous point tracking models cannot correctly.

In the process of task execution, the situation awareness of the human-machine system has a significant impact on task performance[4]. The task design of this study includes explicit tracking tasks and direct data acquisition. Therefore, point tracking error and input aggression were used to evaluate the performance of participants, reflecting their situation awareness.

This study is based on a simple hardware flight simulator. The core of the task design of this study lies in the randomness of the task. In several previous studies about pilot boundary avoidance model[5], [6], periodic tasks were used, which would cause participants to learn the regularity of the task goals and predict the action trajectory of the task goals, thus affecting the objectivity of the experiment and model fitting.

This research investigated pilot’s response to point tracking and boundary avoidance in a simulated flight task, and the main aim of this study lies in the tracking performance and input aggression under different task conditions regarding both point tracking and boundary avoidance tracking.

Method

Figure 1. The joystick used for simulation tasks.

Fourteen participants volunteered and took part in the experiment tests. The joystick utilized in this study had two main sticks. The left stick only moved in vertical direction, simulating the "collective" inceptor for helicopters, and the right stick moved in both vertical and horizontal directions, simulating the "cyclic" inceptor for helicopters. The simulated task was developed and operated on a laptop. The joystick was connected to the laptop using a USB cable from the joystick.

The tasks were designed based on a helicopter tracking task and the concepts of "point tracking" and "boundary avoidance tracking". During the task two types of information were displayed on the monitor, meaning "point" and "boundary".

The GUI was designed in svg format. The participants would see an interface as Figure 2.

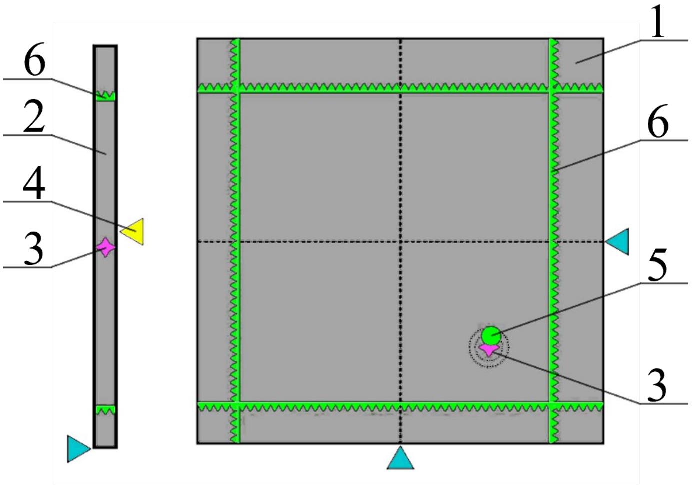

Figure 2. GUI Interface.

Elements displayed in the interface is explained as below:

1. Square scale, indicates the cyclic stick.
2. Vertical scale, indicates the collective stick.
3. Purple diamonds, point tracking target indicators.
4. Triangle indicator, displays the "response" of the participants controlling the collective stick.
5. Dot indicator, displays the "response" of the participants controlling the cyclic stick.
6. Sawtooth boundaries, for boundary avoidance tracking tasks.

Among them, 4 and 5 would change color according to the distance between target and response, as an indicator for the participants to adjust their controlling strategies. 6 would also change color if the response was close to the boundaries.

This research used Simulink module integrated in MATLAB 2022a to generate and output target and boundary movement signals, at the same time transfer input signals. The Simulink terminates the task when participants hit the boundary.

Target movement parameters were set random in a certain limit, consequently, target movements were random. An example of one-axis target movement was shown in Figure 3. During the whole experiment, participants individually experienced a set of unpredictable random tasks, while tasks were consistent among all the participants.

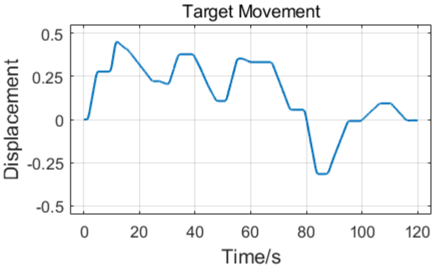

Figure 3. Target Movement.

Boundary movement patterns could be configured as “discrete” or “continuous”. An example of one-axis boundary movement was shown in Figure 4. In the figure, the difference between “discrete” and “continuous” was illustrated.

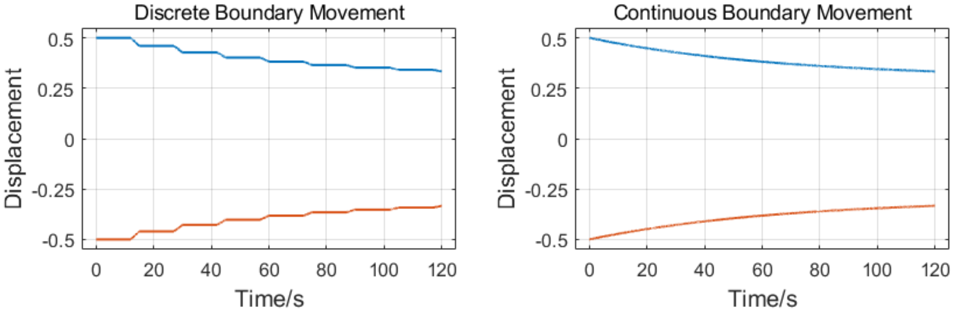

Figure 4. “Discrete” and “continuous” boundary movement.

Shift movement was applied on both target and boundary. Figure 5 shows the boundary movement with shifting.

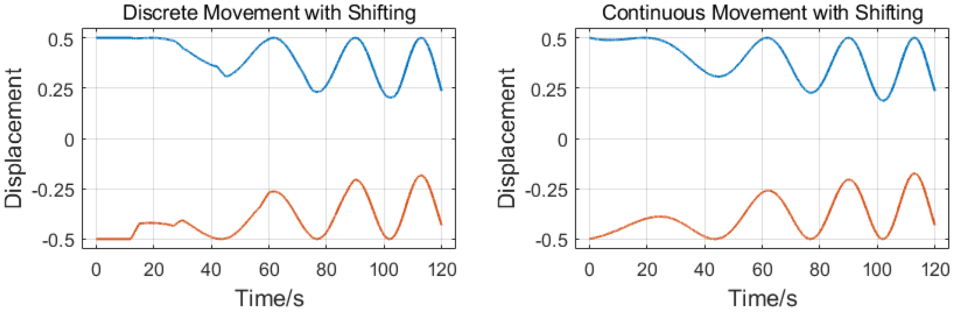

Figure 5. Boundary movement with shifting.

The participants were instructed to operate only the cyclic stick. The participants performed a sequence of 5 different types of tasks, each type 3 runs (except for Task 0 which the participants can repeat as many times as they wished). The types of tasks were described below:

a) Task 0: point tracking task only with no terminate condition other than task duration.

b) Task 1: boundary avoidance task, boundary movement is “discrete”, no shifting.
c) Task 2: boundary avoidance task, boundary movement is “continuous”, no shifting.
d) Task 3: boundary avoidance task, boundary movement is “discrete” with shifting.
e) Task 4: boundary avoidance task, boundary movement is “continuous” with shifting.

In this study, tracking error and input aggression was utilized to evaluate the performance and control strategy of the participants. The calculation of these indicators is as below:

$$\text{error} = \text{target} - \text{response} \qquad (1)$$

$$\text{aggression} = \sqrt{\frac{1}{t_1 - t_2}\int_{t_1}^{t_2} \left|\dot{\delta}(\mathrm{t})\right|^2 dt} \qquad (2)$$

where:
target – sequence of target movement signals.
response – sequence of response signals.
$\delta(\mathrm{t})$ – sequence of input signals, and $\dot{\delta}(\mathrm{t})$ is the time derivative.
t_1, t_2 – starting and ending time of a time interval for analyzing aggression.

To evaluate the performance and aggression in certain period (whole task run, or specific condition, for example), the root mean square value of error and aggression is calculated:

$$\text{errorRMS} = \sqrt{\frac{1}{n}\sum_i \text{error}_\mathrm{i}^2} \qquad (3)$$

$$\text{aggressionRMS} = \sqrt{\frac{1}{n}\sum_i \text{aggression}_\mathrm{i}^2} \qquad (4)$$

Different “conditions” were defined to distinguish different groups of situations the participants encountered during the tasks:

a) Group 1
“*Approach*”: The dot moves towards one of the boundaries.
“*Leave*”: The dot moves in a reversed direction of one of the boundaries.
b) Group 2
“*Near*”: The dot locates between one of the boundaries and “boundary thresholds”.
“*Away*”: The dot locates outside boundary thresholds.
c) Group 3
“*Approach and Near*”: Conditions that meet both “*Approach*” and “*Leave*” at the same time.
“*Leave or Away*”: Conditions that meet “*Leave*” or “*Away*”.

Figure 6 demonstrates the above conditions in an intuitive way.

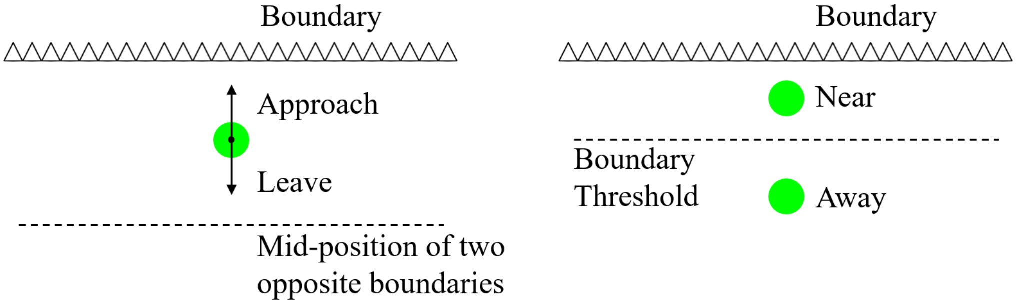

Figure 6. Demonstrations of “conditions”.

The analysis of this paper is based on a boundary threshold of 0.1. which is low capture difficult tasks, and large enough to sample enough amount of data to be analyzed.

Statistical analyses were done with task runs that didn’t fail, to extract data that fully represented participants performances under pressure.

Results

a) Group 1

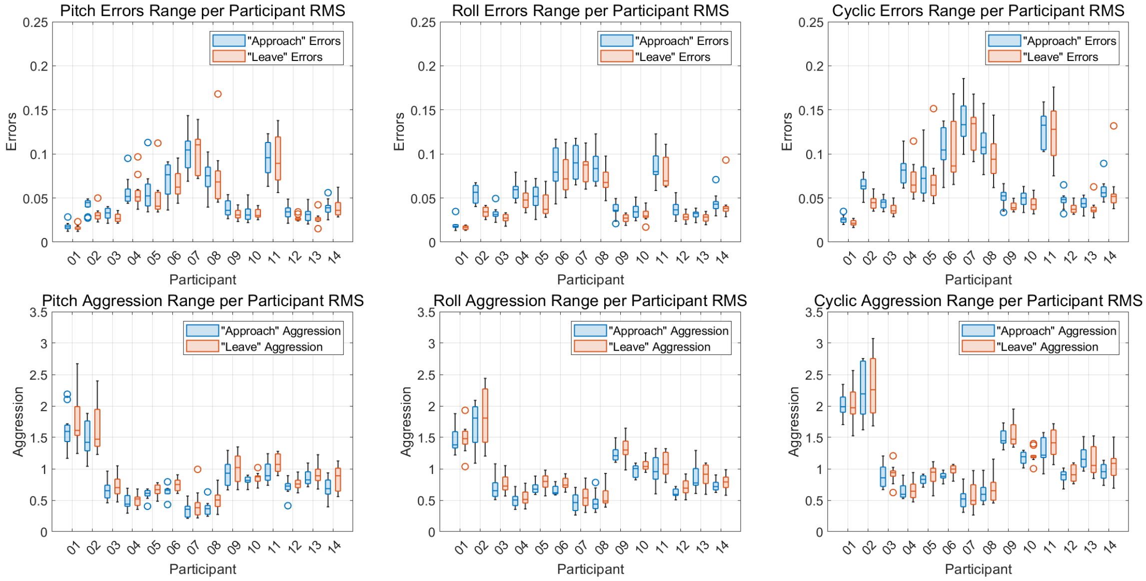

Figure 7. Error and Aggression under "Approach" and "Leave" conditions.

Table 1. ANOVA analysis between "Approach" and "Leave" Conditions

Difference Significance: Approach and Leave Conditions								
Tracking Error								
Pitch			**Roll**			**Cyclic**		
Source	**F-value**	**P-value**	**Source**	**F-value**	**P-value**	**Source**	**F-value**	**P-value**
Condition	4.15	0.042	Condition	33.78	<0.001	Condition	13.80	<0.001
Participant	58.58	<0.001	Participant	70.93	<0.001	Participant	76.19	<0.001
Condition*Participant	0.29	0.993	Condition*Participant	1.03	0.421	Condition*Participant	0.45	0.951
Input Aggression								
Pitch			**Roll**			**Cyclic**		
Source	**F-value**	**P-value**	**Source**	**F-value**	**P-value**	**Source**	**F-value**	**P-value**
Condition	18.32	<0.001	Condition	14.38	<0.001	Condition	4.97	0.027
Participant	89.52	<0.001	Participant	98.80	<0.001	Participant	132.63	<0.001
Condition*Participant	0.42	0.963	Condition*Participant	0.17	1.000	Condition*Participant	0.24	0.997

The tracking errors under "*Approach*" condition were slightly larger than that under "*Leave*" condition for most participants. But the results showed no statistical significance ($p>0.05$). The input aggressions under "*Approach*" condition were slightly larger than that under "*Leave*" condition, though the significance of the difference is not observed ($p>0.05$).

The result showed that participants were more likely to control the stick less aggressively when they tried to follow the target that was getting close to the boundary to avoid hitting the boundary.

b) Group 2

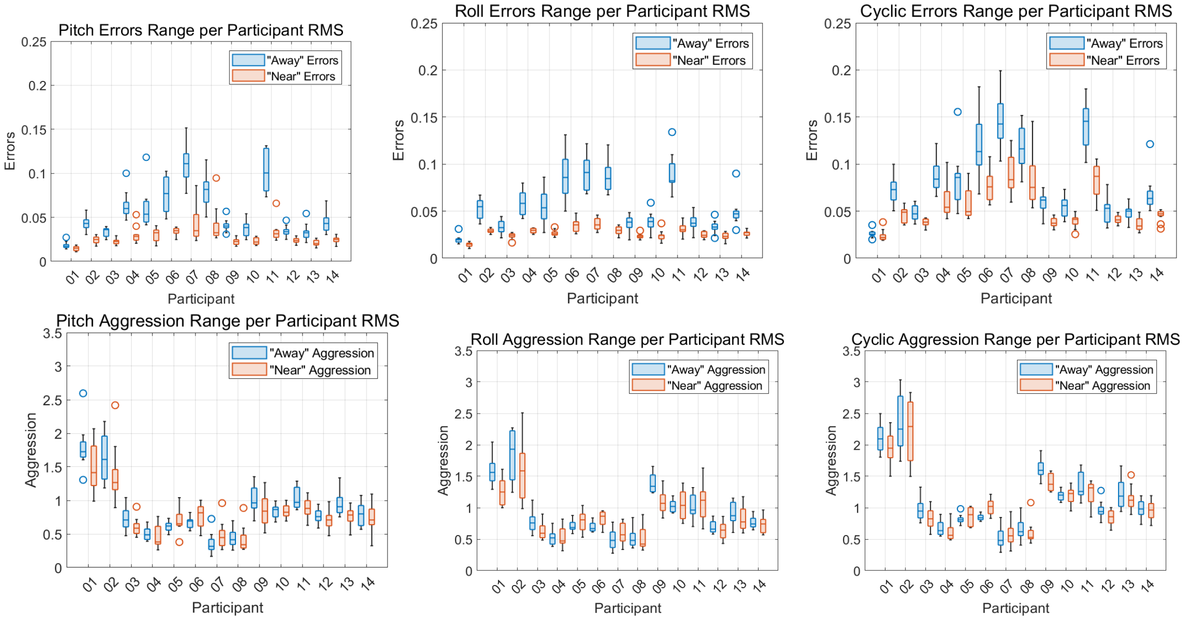

Figure 8. Error and Aggression under "Near" and "Away" conditions.

Table 2. ANOVA analysis between "Near" and "Away" Conditions

Difference Significance: Near and Away Conditions								
Tracking Error								
Pitch			**Roll**			**Cyclic**		
Source	**F-value**	**P-value**	**Source**	**F-value**	**P-value**	**Source**	**F-value**	**P-value**
Condition	335.44	<0.001	Condition	519.03	<0.001	Condition	162.14	<0.001
Participant	43.93	<0.001	Participant	44.27	<0.001	Participant	63.15	<0.001
Condition*Participant	13.48	<0.001	Condition*Participant	19.71	<0.001	Condition*Participant	5.24	<0.001
Input Aggression								
Pitch			**Roll**			**Cyclic**		
Source	**F-value**	**P-value**	**Source**	**F-value**	**P-value**	**Source**	**F-value**	**P-value**
Condition	12.34	<0.001	Condition	10.77	0.001	Condition	9.26	0.003
Participant	70.31	<0.001	Participant	72.41	<0.001	Participant	142.73	<0.001
Condition*Participant	2.10	0.014	Condition*Participant	3.04	<0.001	Condition*Participant	1.10	0.355

The tracking errors under "*Near*" condition are significantly lower than that under "*Away*" condition ($p<0.001$) for all participants. Participants' behavior during the test runs showed that they exerted greater effort to control the stick, maintaining point tracking task while prevent hitting the boundary.

The input aggressions presented inconsistent results. For some participants, the input aggressions were larger under "*Near*" condition, others were lower. The difference of the input aggressions was significant ($p<0.05$).

c) Group 3

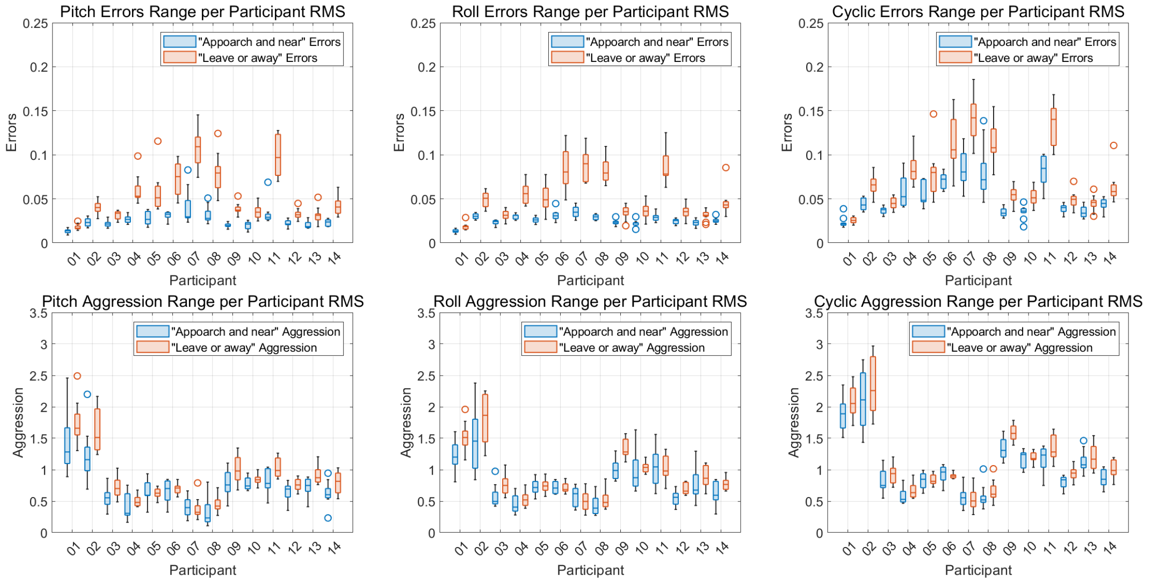

Figure 9. Error and Aggression under "Approach and Near" and "Leave or Away" conditions.

Table 3. ANOVA analysis between "Approach and Leave" and "Near or Away" Conditions

Difference Significance: Approach and Near and Leave or Away Conditions								
Tracking Error								
Pitch			**Roll**			**Cyclic**		
Source	**F-value**	**P-value**	**Source**	**F-value**	**P-value**	**Source**	**F-value**	**P-value**
Condition	392.54	<0.001	Condition	537.74	<0.001	Condition	167.23	<0.001
Participant	45.36	<0.001	Participant	50.57	<0.001	Participant	68.64	<0.001
Condition*Participant	15.91	<0.001	Condition*Participant	23.29	<0.001	Condition*Participant	5.79	<0.001
Input Aggression								
Pitch			**Roll**			**Cyclic**		
Source	**F-value**	**P-value**	**Source**	**F-value**	**P-value**	**Source**	**F-value**	**P-value**
Condition	42.93	<0.001	Condition	35.88	<0.001	Condition	25.72	<0.001
Participant	62.66	<0.001	Participant	66.40	<0.001	Participant	140.93	<0.001
Condition*Participant	1.95	0.025	Condition*Participant	2.11	0.014	Condition*Participant	1.01	0.444

The tracking errors under "*Approach and Near*" and "*Leave or Away*" condition showed a similar trend as under "*Near*" and "*Away*" condition mainly because tracking errors under "*Approach*" condition and "*Leave*" condition showed no significant difference. The difference of tracking error here also showed statistical difference ($p<0.001$). Inconsistent results were also observed for aggression under this group. The difference between conditions and participants are significant for pitch and roll axis($p<0.05$), but not the composed cyclic($p>0.05$). Different participants applied different input strategies under severe task conditions, resulted in different point tracking performance.

Conclusion

This research featured a simulation task design based on the concepts of point tracking and boundary avoidance tracking, and data analysis method to investigate pilots' point tracking performance and input aggression. Several results could be drawn from this study. Since the boundary avoidance tracking was introduced to the task, participants presented different input strategy indicated as aggression, and resulted in different tracking error. When the target was near the boundary, the participants presented significantly lower tracking errors ($p<0.001$), and the input aggressions are also lower for the pitch and roll axis respectively ($p<0.05$). In summary, this research demonstrated the relationship among task condition, input strategy, and task performance.

Task design, data analyzing method, and results could inspire related research in pilot's biodynamic feedthrough, human-machine interaction, and rotorcraft-pilot coupling.

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