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Control of a Lateral Helicopter Side-step Maneuver on an Anthropomorphic Robot

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Our society relies more and more on flight simulation for pilot training to enhance safety and reduce costs. But to meet the highest level of general technical requirements for simulators set forth by the FAA and EASA requires high-cost equipment. To make simulator use more accessible, reduced costs might be achieved with novel simulator designs and/or through research to improve the performance of existing designs. This report explores the use of such a novel design, based on an anthropomorphic robot arm to reproduce an experiment designed to evaluate flight simulator motion requirement for helicopter pilot training. Results compare promisingly well to those from a large, high-performance facility where the original work was performed.

I. Introduction

Modern flight training relies increasingly on simulator technology to reduce costs and enhance safety[1,2], since simulators provide a flexible, efficient and safe environment at a much lower cost than real flight[3]. Pilots conduct a major part of their training, maintain their flying skills and even renew their licences through simulator tests[4].

Confidence in a simulator as a valid tool for research and training depends upon the ability of the simulator to provide adequate motion cues to the pilot, i.e., its ability to induce adequate human performance for a given task and environment[5,6]. Because of the limited kinematic envelope for all motion systems, other than actual aircraft, motion drive algorithms are required to provide the best use of the available motion envelope[7]. This optimization depends on an accurate set of motion fidelity criteria for the required task, but there is controversy surrounding this issue[8,9,10].

To develop motion platform requirements and fidelity criteria for flight simulation of several helicopter maneuvers, Schroeder[12] performed a series of experiments on the Vertical Motion Simulator at NASA Ames Research Center. He measured both objective performance responses and subjective evaluation the simulator, self-performance, and perceived motion fidelity. He uses the results, along with results from previous research to propose fidelity criteria for helicopter flight simulation.

In a companion paper, development of a novel motion simulator, the MPI Motion Simulator, based on an anthropomorphic robotic arm, is presented[11]. Due to the larger motion envelope and superior ability to combine rotation with translation, when compared with similarly priced conventional Stewert platforms, an initial test of the suitability of the new setup for simulator research was performed.

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II. Experiment

A. Task and participants

Participants performed constant-altitude side-steps between two targets presented along an arc centered at the simulator base. Both left and right side-steps were performed. At the beginning of each trial, participants were required to hover until they had acquired a steady position at the starting point. When a button on the center stick was pressed, the target moved a constant distance either to the left or right. Participants had to perform a side-step towards the new target position attempting to optimize control, accuracy with respect to the target, and hover performance at the final target. After arriving at the final position, subjects needed to hover in front of the target stably for approximately 5 seconds before they pushed the button on the center stick again, which brought the simulator back to the starting position. After each such trial, participants gave a rating on their own performance, the simulator motion fidelity, and on the Cooper-Harper Handling Qualities Ratings scale. In total, seven participants completed the experiment. Two additional subjects didn't complete the experiment due to motion sickness. All are members of the Max Planck Institute for Biological Cybernetics.

B. Apparatus

The experiment was performed on the MPI Motion Simulator[11] that is based on the Kuka Robocoaster (Kuka Roboter GmbH, Germany), see Figure 1. The Robocoaster is a 3-2-1 serial robot with a large motion envelope. The simulator has the capability to move with all six degrees of freedom, but for this experiment the participants are translated along an arc using the axis of rotation from the simulator base and are supplied with cues on rolling motion. As in Schroeder[12], the center of rotation for the role motion was located near the abdomen of the participants.

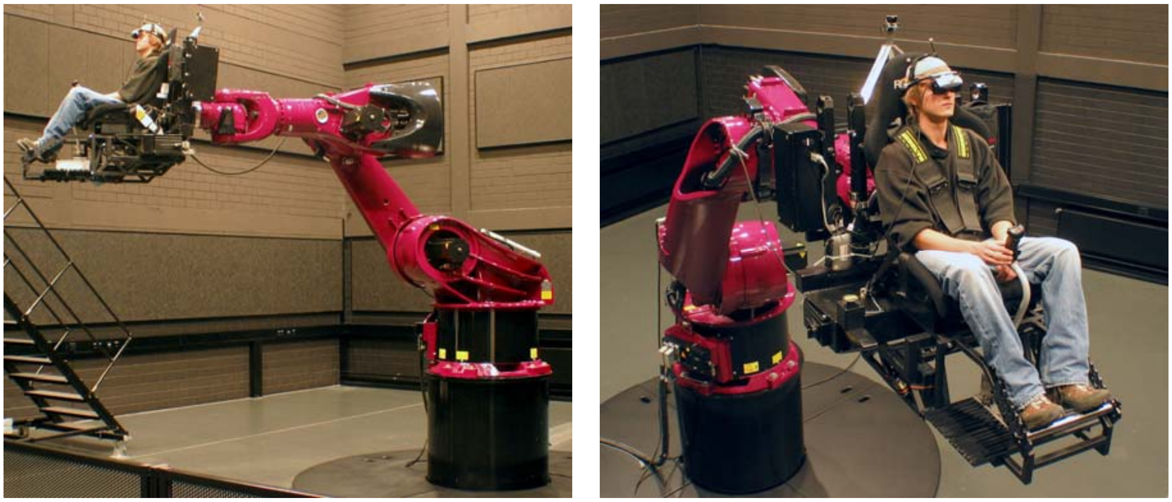


Figure 1. The MPI Motion Simulator.

The dynamics of the simulated helicopter are inspired by the dynamics from Schroeder[12] and have two degrees of freedom. Altitude of the center of rolling motion remained constant at 2.66 m, which is also the height of the participants above the ground in the real world; pitch and yaw with respect to the arc remained zero. The equations of motion are given as:

$$\ddot{\phi} = -10 \cdot \dot{\phi} + 8 \cdot K_{roll} \cdot \delta_{lat}\ , \text{ Eq. 1}$$

$$\ddot{\theta} = -12.5 \cdot \dot{\theta} + 20 \cdot K_{lat} \cdot \sin\left(\frac{\phi}{K_{roll}}\right), \text{ Eq. 2}$$

where ϕ is the roll angle, δ_{lat} is the displacement of the center stick (normalized from -1 to 1), and θ is the rotation of the simulator base. The original coefficients were slightly modified from Schroeder[12] based on feedback from two experienced helicopter pilots at the institute. Their impression of what felt closest to a real helicopter was used to tune the parameters.

The motion gains K_{roll} and K_{lat} are also given in Equations 1 and 2, and only scale the motion cues from the system dynamics. As there is no frequency dependency of the motion filters, the motion of the simulator is in phase with the visual presentation. The gains of the motion channels are varied systematically according to the same scheme used by Schroeder[12] with one additional combination (K_{roll} and K_{lat} both equal to 0.2), as shown in Table 1.

The visual cues were presented through a Head Mounted Display (HMD) (eMagin, USA) with a diagonal field of view of 40°. Participants controlled the helicopter dynamics with a center stick that is custom combination of a G-Stick (Flight-Link, USA) and a FlyBox (BG Systems, USA).

Table 1: Experimental motion conditions.

Condition	K_{lat}	K_{roll}
1	0.0	0.0
2	0.2	0.2
3	0.4	0.2
4	0.4	0.4
5	0.4	0.6
6	0.6	0.2
7	0.6	0.4
8	0.6	0.6
9	0.8	0.2
10	0.8	0.4
11	0.8	0.6
12	1.0	1.0

C. Experimental procedure

The experiment was carried out with non-pilots. In order to be able to use subjective ratings, participants needed to have a frame of reference and a baseline condition upon which to make their judgments. Therefore, participants were trained on the simulator, but without distortion of motion cues and without the HMD. They were instructed to consider this “real world” experience as the baseline for all judgments. Generally, participants quickly learned to control the dynamics and perform the hovering and side-step task with sufficient performance.

The experiment consisted of 4 blocks. Before the experiment, participants had to hover and make side-step maneuvers in the real world for a minimum of 10 minutes, but were allowed to take as long as they felt was necessary to be familiar with “the real helicopter”. Each block lasted approximately 15 minutes and contained all motion conditions, which were presented randomly. Participants had to perform a balance of both left- and rightward side-step maneuvers. After each trial, the participants gave their subjective ratings. They had to report on their own performance with a rating of 1 (good), 2 (adequate), or 3 (inadequate). The motion fidelity was rated either 1 (comparable to real world), 2 (different from the real world, but not distracting), and 3 (different from the real world and distracting). Finally, participants were asked to give a rating on the Cooper-Harper Handling Qualities Rating Scale, as modified by Schroeder[12]. This scale consists of values from 10 (uncontrollable) to 1 (highly desirable and excellent aircraft characteristics). After each block, participants could rest and, before beginning the next experimental block, were required to perform the “real world” hover and side-step maneuvers for at least 5 minutes.

D. Independent variables and dependent measures

The independent variables in this experiment are the motion gains for the roll and lateral motion. These are varied systematically to uncover their effect on subjective ratings and objective measures.

Subjective ratings are given in three categories: a rating of performance, a rating of the motion fidelity with respect to the motion experienced before starting the measurements, and a rating based on the Cooper-Harper Handling Qualities Rating Scale. The objective measures are based on the control behavior of the participants and include positioning performance and control activity. These measures are calculated from control and position signals that are measured and recorded during each experimental trial.

III. Results and discussion

The results are divided into two categories: objective measurements, which include signals measured during the experiment, and subjective ratings, which were given by the participants after each experimental trial.

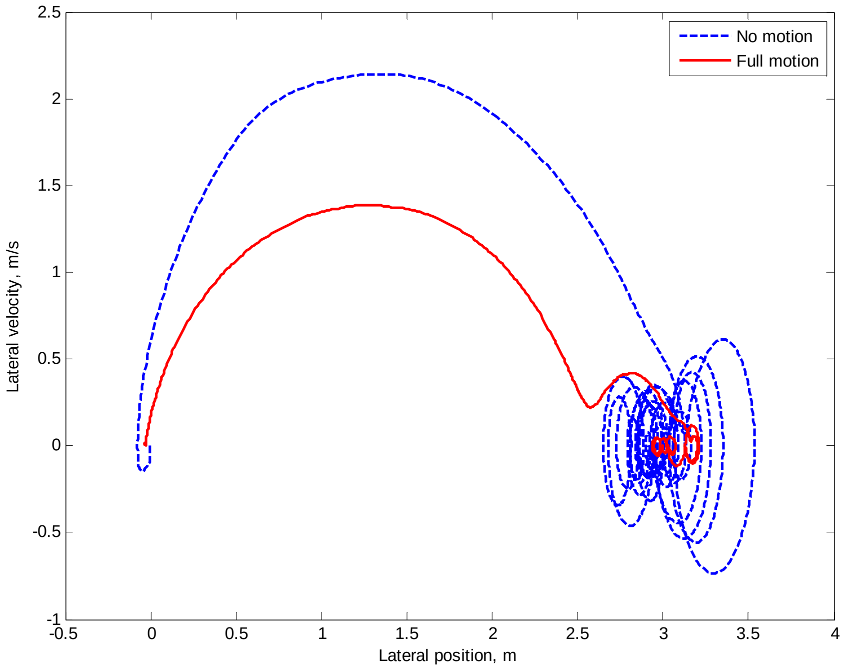


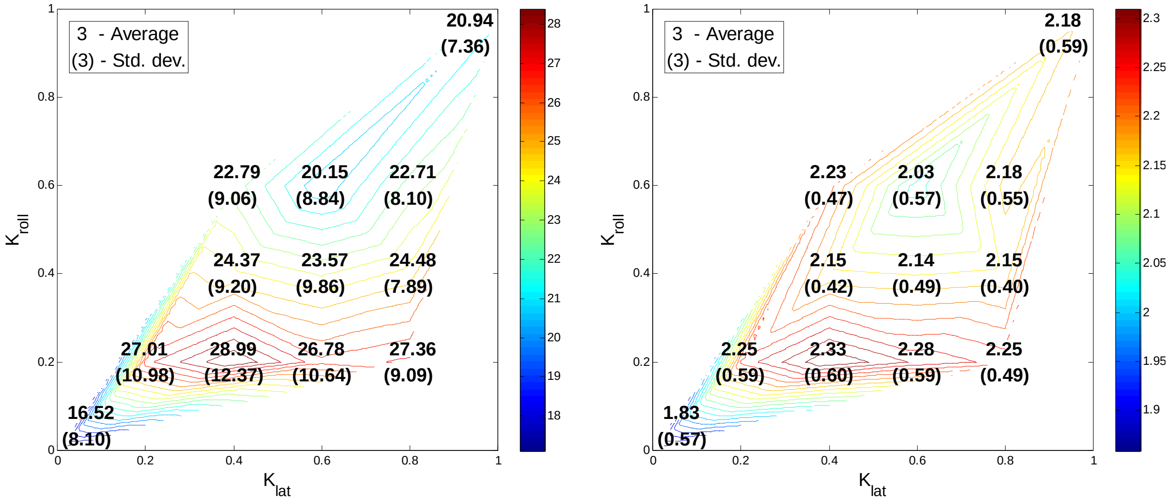
Figure 2. Phase space plot of lateral velocity versus position, with and without motion.

Each participant performed twelve conditions in which the motion gains of the simulator were varied systematically, see Table 1. The conditions were repeated four times, two side-steps to the right and two to the left to balance out effects that direction might have.

A. Objective data

The objective measures include the Root Mean Squared (RMS) value of the lateral stick position, lateral stick position rate, and lateral helicopter position at the final target. These measures on pilot activity are calculated from the time when the target starts to move to the end of the trial. The lateral helicopter position at the final target is for the final 5 seconds of each trial. A representative phase space plot of the lateral simulator position and velocity is shown in Figure 2.

Figure 3 gives the RMS value for the lateral stick position and velocity for all participants and trials, with the standard deviation given in parentheses. It is clear that when transitioning from full to less motion, larger control inputs of the participants were elicited. This is because the participants now need to generate lead information about their motion from the visual display instead of from the motion cues they feel[13]. This is consistent with the findings from Schroeder[12].

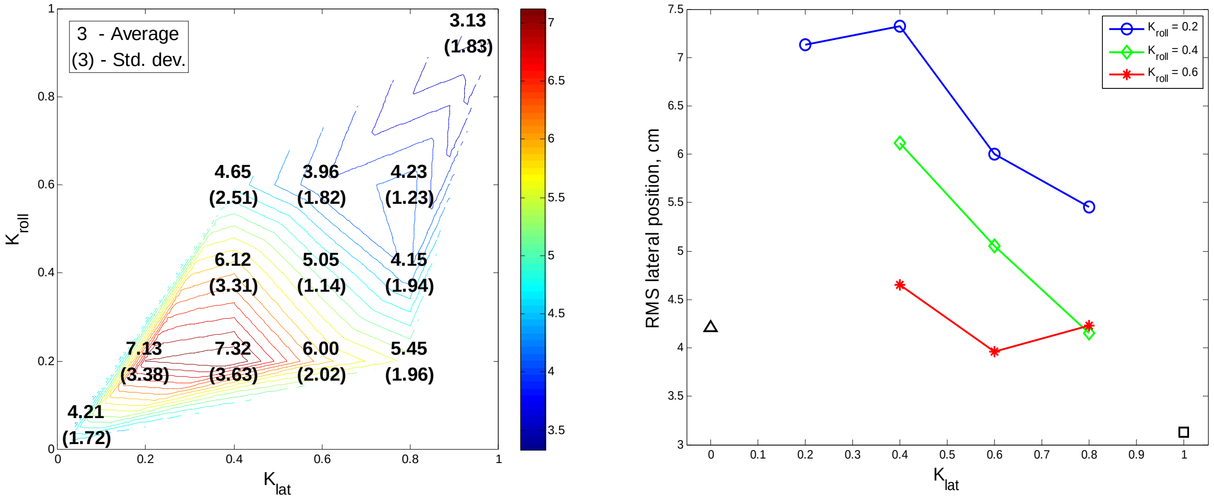


(a) Lateral stick position, percent of full range.

(b) Lateral stick rate, percent/s

Figure 3. RMS values of the stick movement.

However, the condition without motion feedback shows a decrease in lateral stick position and stick position rate compared to the conditions with motion. This is surprising, since most participants verbally commented with strong disapproval of this experimental condition. Apparently, this disapproval did not lead to larger control inputs and might indicate that although the condition was unpleasant, it was either easier to control or control movements led to unpleasant simulator responses. These data are different from those of Schroeder[12], who found an increase in stick RMS values with no motion.



(a) Contour plot. K_{roll} versus K_{lat}.

(b) RMS lateral position versus K_{lat}

Figure 4. RMS values of lateral helicopter position, cm.

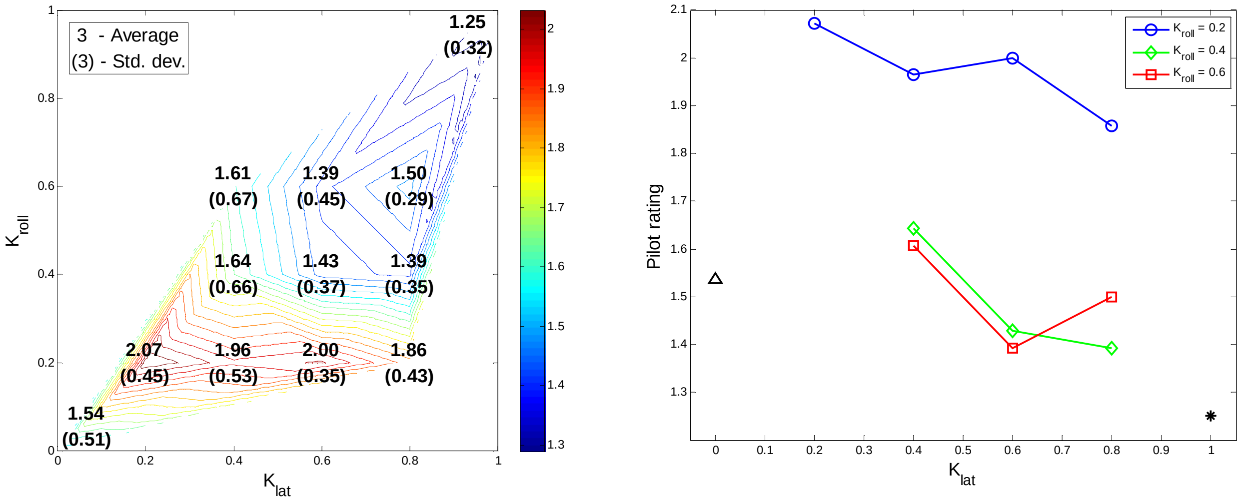
Lateral hover performance is evaluated with the RMS value of the lateral helicopter position in the last 5 seconds of each trial. The average across subjects and trials and the standard deviation are given in Figure 4. It is clear that in the case of full motion, the hover performance is best. With decreasing motion, the performance gets worse, with a minimum in performance at the condition with the lowest non-zero motion gains. When participants perform the task without motion feedback, the performance is just marginally worse than with full motion feedback. Apparently, reducing the gains of the motion feedback acts as a disturbance and actively prohibits the participants from performing the task well. When the source of conflict with the visual feedback is taken away, the task can be performed better again.

B. Subjective data

The pilot performance ratings indicate how well a trial was performed according to the participants. The scale consisted of three numerical levels: 1 (good), 2(adequate), and 3 (inadequate). Figure 5 gives the results averaged across all participants and trials.

The performance rating shows the same trend as the RMS of the stick position. Participants rate their performance in conditions with full motion cues the best. Performance in the condition without motion is rated better than the conditions with low motion gains.

When looking at an increase in lateral motion gain with respect to the roll motion gain, the ratings on pilot performance indicate that an increase in roll motion gain is better than increasing the lateral motion gain. This is especially true in the region with low motion gains.

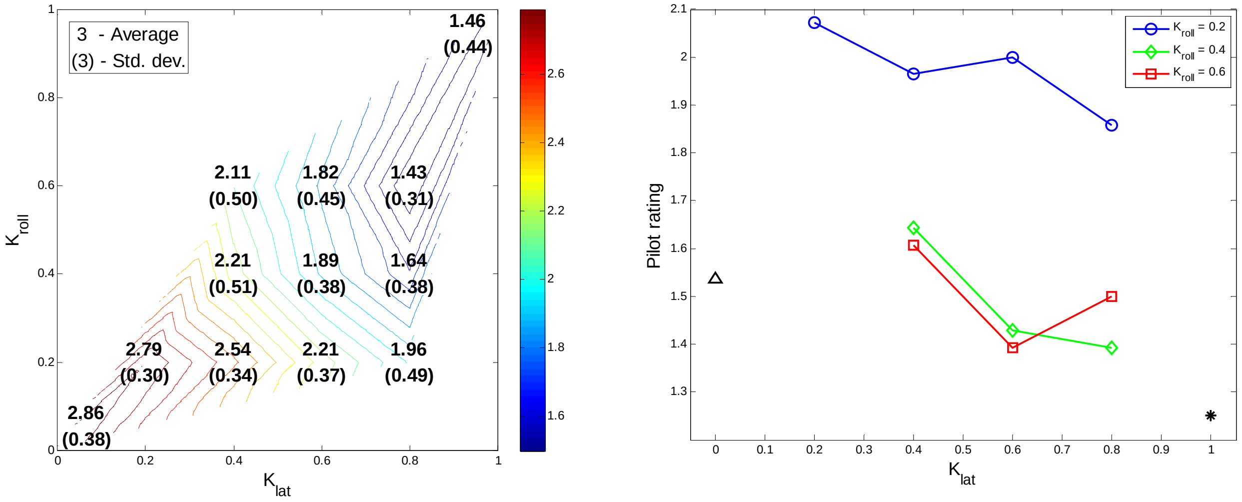


(a) Contour plot. K_{roll} versus K_{lat}.

(b) Pilot's self-rating versus K_{lat}

Figure 5. Participant rating on performance.

The motion fidelity ratings also consisted of three numerical levels: 1 (comparable to real world), 2 (different from the real world, but not distracting), and 3 (different from the real world and distracting). Participants were instructed to compare the motion fidelity with the motion behavior in the hover task in the "real world" without any motion distortion.

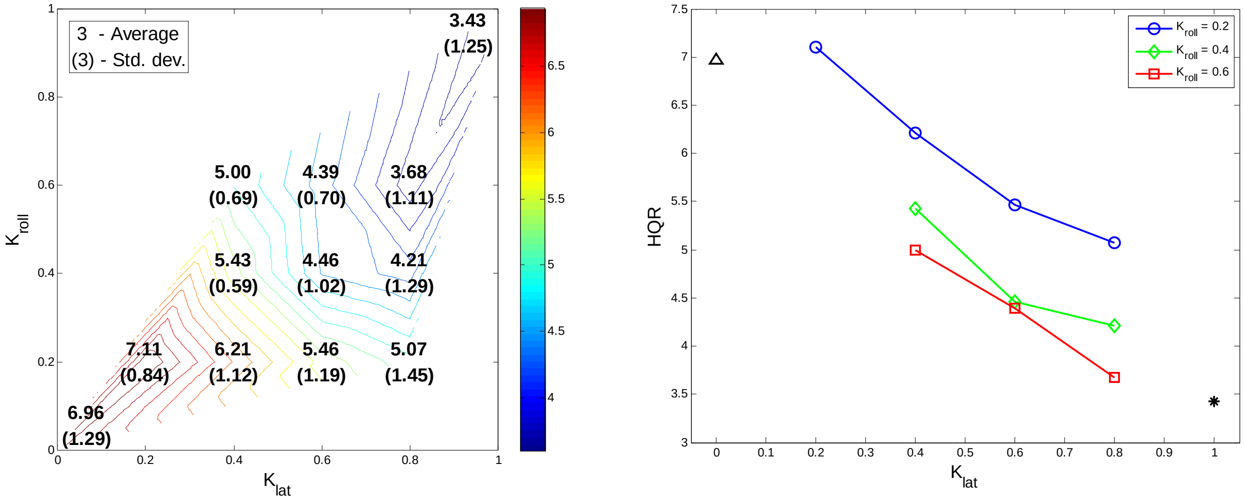


(a) Contour plot. K_{roll} versus K_{lat}.

(b) Motion fidelity ratings versus K_{lat}

Figure 6. Motion fidelity ratings.

Figure 6 gives the average of the motion fidelity ratings over all participants and trials and the standard deviation. Not surprisingly, the condition without motion was almost always rated as inadequate. With increasing motion, the ratings also increased.



(a) Contour plot. K_{roll} versus K_{lat}.

(b) Motion fidelity ratings versus K_{lat}

Figure 7. Cooper-Harper Handling Qualities Ratings.

The Cooper-Harper Handling Qualities Ratings are plotted in Figure 7. Again, the lower the motion gains, the worse the rating gets. The trend is very similar to the motion fidelity ratings given in Figure 6 and the hover performance given in Figure 4. With lower motion gains, pilots change their control strategy by increasing their control action. This increases workload, whereas performance does not increase. Thus the ratings on Handling Qualities become worse.

IV. Conclusion

Although there were several important differences between this experiment and that of Schroeder[12], the main results were reproduced. These experimental differences include the use of non-pilots, a small field-of-view HMD, and lateral motion on an arc, rather than a straight line. It is unclear why the performance of the subjects was quite good with no motion, but it may relate to the lack of experience in comparison to the professional pilots used by Schroeder[12].

The results also demonstrate the application of the new MPI Motion Simulator for helicopter flight simulation research. With planned improvements to expand the motion envelope and improve visualization[11], continued research, including the use of trained pilots, is planned

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