MULTILOOP MANUAL CONTROL OF DYNAMIC SYSTEMS

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ABSTRACT

Modern, high performance aircraft increasingly rely upon high-authority stability and command augmentation systems to achieve satisfactory performance and handling qualities. In addition, certain tasks which have traditionally been allocated to the human pilot are candidates for automation in the near future. This situation has accentuated a long-standing need for a thorough understanding of the human's capabilities, limitations and preferences when interacting with complex dynamic systems, particularly when the question of task allocation between man and machine arises. In this work, an analytical and experimental study was undertaken to investigate human interaction with a simple, multiloop dynamic system in which the human's activity was systematically varied by changing the levels of automation. The control loop structure resulting from the task definition parallels that for any multiloop manual control system, and hence, can be considered as a stereotype. The analytical work concentrated upon developing simple models of the human in the task, and upon extending a technique for describing the manner in which the human subjectively quantifies his opinion of task difficulty. The experimental work consisted of a man-in-the-loop simulation providing data to support and direct the analytical effort.

INTRODUCTION

Automation has become a central issue in the design of man-machine systems in the past decade, particularly as regards manned aircraft. The pilot's role as a systems manager or supervisor is being emphasized as the capabilities of modern avionics systems, in particular, digital computers, evolve. Indeed man-machine interaction has become nearly synonomous with man-computer interaction in describing the activity of the pilot in the cockpit of the future.

It is worth emphasizing that the fundamental role of the human in the aircraft cockpit is still that of a "controller" in that nearly all his activity has, as its ultimate aim, the control of the vehicle's velocity vector.

A convenient means of explaining the nature of tasks involving the manual or automatic control of dynamic systems such as aircraft is shown in Fig. 1. Here, Ω_i represents a generalized "bandwidth" indicating the relative time scales involved in each of the loop shown. The nesting of feedback loops with $\Omega_1 > \Omega_2 > \Omega_3 \ldots > \Omega_n$ is a characteristic of nearly all dynamic control systems, no matter how complex. As an example of an aircraft flight control problem, the loops of Fig. 1 could be interpreted as follows: The block denoted Ω_1 represents attitude control with a relatively high bandwidth. Block Ω_2 represents altitude control with a lower bandwidth while block Ω_3 represents navigation activity with a still lower bandwidth.

The ways in which a man and a computer can interact in the system of Fig. 1 can be quite subtle and have been outlined, classified and discussed by Rouse [1]. They are obviously dependent upon which function are under manual and which are under computer (automatic) control. Figure 1 invites a simple and practical allocation of tasks between man and computer (manual and automatic control). One can start at the inner-most loop and begin automating the feedback activity loop-by-loop. This means that the human is responsible for fewer loop closures as the automation proceeds and these with lower and lower bandwidths. Conversely, one can start at the outer-most loop and begin the automation process. Again, as the automation proceeds, the human is responsible for fewer loop closures, but the bandwidth of the manual control task is, in this case, dominated by the inner-most loop. Both of these schemes are consistent with current practice in aircraft flight control automation. For example, the first is exemplified by an automatic landing system while the second is exemplified by the same landing task, except using a cockpit flight director. Both schemes can result in increased man-machine performance and decreased "workload".

It is of some interest to analyze these two automation approaches, particularly when outer-loop preview information is available to the human. To this end, an analytical and experimental study was undertaken to investigate human interaction with a simple, multiloop dynamic system in which the human's activity was systematically varied by changing the level of control augmentation (automation level). The control loop structure resulting from the task definition is consistent with that of Fig. 1 and, as such, can be considered as a simple steroetype. The analytical work concentrated upon developing simple models of the human in the task, including preview effects, and for extending a technique for describing the manner in which the human subjectively quantifies his opinion of task difficulty [2] . The experimental work consisted of a man-in-the-loop simulation providing data to support and direct the analytical effort.

EXPERIMENT

A simple man-in-the-loop simulation was conducted on a fixed-base laboratory type simulator at NASA Ames Research Center. The actual task considered was that of the longitudinal control of a hovering helicopter or VTOL vehicle. The multiloop system is shown in Fig. 2. This figure indicates completely manual operation in its present form and the basic vehicle possesses so-called rate-command, attitude-hold pitch attitude dynamics. Vehicle attitude determines vehicle velocity, which, in turn, determines vehicle displacement from some command position. Figure 2 also outlines the automation levels which were examined in this study. If the inner-most loop of Fig. 2 is automated, the human is left with an attitude-command, attitude-hold "inner" loop, with velocity and position loops unchanged. If the next inner-loop of Fig. 2 is also automated, the human is left with a velocity-command, position-hold system. Finally, by automating all the loops of Fig 2 but leaving the pilot the option of providing a position-command signal to the automated system, a position-command, position-hold system results. Conversely, of the outer-most loops are closed and an inner-loop command signal displayed to the pilot, a flight director system results (not indicated in Fig. 2).

The unagumented vehicle dynamics were very simple and can be given as:

$$\dot{x} = u$$

$$\dot{u} = -g\theta + X_u u$$

$$\dot{\theta} = K\delta$$

where x represents vehicle position, u vehicle velocity, θ vehicle attitude and δ control deflection.

A color, raster-type display was used in the experiment to provide the subjects with the pertinent information needed to close the loops in Fig. 2. The display format is shown in Fig. 3. An isometric manipulator was used in all but the position command configuration where an unrestrained finger manipulator was employed. Each of the automated closures were implemented in a manner similar to that which would be employed by the human were he asked to close the loops in question.

The human pilot dynamics were estimated by using the simplifed crossover model of the human [3] for each loop closure:

$$Y_{p_i} Y_{c_i} = (\omega_{c_i}/s)e^{-\tau_e s} \quad (1)$$

where Y_{p_i} represents the human pilot dynamics in the closure in question, Y_{c_i} represents the pertinent vehicle dynamics in that closure, and ω_{c_i} represents the open-loop crossover frequency (or closed-loop bandwidth). For example, the attitude-command system was implemented by allowing Y_{p_θ} in Fig. 2 to take the form

$$Y_{p_\theta} = \omega_{c_\theta}/K$$

where ω_{c_θ} is the appropriate crossover frequency and K is the gain appearing in θ/δ. Of course, the human's effective time delay τ_e was deleted in implementing the automated loop closures.

The command signal x_c was chosen as a square wave with a fundamental frequency of 0.2 rad/sec. This command signal was displayed to the subject in preview fashion as the horizontal translation of the square waveform on the display of Fig. 3. The amplitude of the command signal was 50 ft. The loop crossover frequencies were chosen by equating the position-loop crossover frequency, ω_{c_x}, to that of the fundamental component of the command signal and then separating the remaining crossover frequencies by a factor of three. This factor was suggested by other multiloop manual control experiments [4].

The position command signal was chosen as periodic to encourage higher levels of skill development on the part of the subjects.

Four naive subjects participated in the experiment. Each simulation run lasted approximately 95 seconds. Each subject saw the 5 different configurations presented in the following order: (1) velocity command, (2) rate command, (3) flight director, (4) attitude command, and (5) position command. Root-mean-square (RMS) performance scores were recorded as were pilot opinion ratings of task difficulty quantified on a non-adjectival rating scale [5]. The subjects were instructed to minimize position errors while maintaining realistic vehicle pitch rate. The quantify the latter, an audio alarm sounded whenever $\dot{\theta}$ exceeded 10 deg/sec. Data was taken only after RMS performance scores stabilized.

RESULTS

Figure 4 summarizes the outer-loop position performance for the subject with the best performance (subject 3) for each configuration. The unfilled symbols in Fig. 5 show the subjective task difficulty ratings for each configuration averaged across all the subjects. A technique for obtaining objective measures of task difficulty from analysis of control movements was investigated [6]. Specifically, the number of individual "control movements" during any run were measured and recorded. As implemented in this study, a "control movement" was said to occur when the subject's control input exceeded a criterion value defined as a percentage of the RMS value of the output for that run. A criterion value of 75% was found to produce trends in the control movement data which compared well with those of the subjective opinion data with the exception of the flight director. This discrepancy will be discussed in the next section. The control movement results are shown in Fig. 6 for each configuration, averaged across all subjects.

Figure 7 shows typical time responses in x, u, and θ for subject 3 for each of the automation configurations. This figure also demonstrates one of the most important results of the experimental study. Namely, with the exception of the flight director, all configurations allowed the subjects to synchronize the vehicle position x(t) with the command input $x_c(t)$. Since the flight director was the only configuration which forced compensatory behavior on the part of the subjects, the remaining configurations apparently allowed higher levels of skill development associated with preview tracking.

PILOT MODELING

A simple pilot modeling effort was undertaken to identify, at least approximately, the pertinent model parameters in the completely manual system of Fig. 2. An off-line computer simulation of that system was implemented. Nominal pilot models of the following form were examined:

$$Y_{p_\theta} = \omega_{c_\theta} e^{-\tau_e s} = 1.8e^{-0.3s}$$

$$Y_{p_u} = \omega_{c_u} = 0.6 \qquad (2)$$

$$Y_{p_x} = \omega_{c_x} = 0.2$$

It was found that no choice of the parameters in Eq. (2) would yield model time responses that provided adequate matches to the data, even when the command input x_c was advanced in time to model preview. However, when the actual square wave time history for x_c was replaced with the position command which the subject generated in using the position command system, a dramatic improvement was seen in the modeling results. Fig. 8 comapres the subject-generated position command for subject 3 with tha actual square wave position command. It should be noted that all the subjects generated commands which were similar in nature to that of Fig. 8 when using the most automated, position command system. An accurate approximation to the subject-generated position command was implemented in the off-line computer simulation using the pilot model of Eqn, (2) with the nominal parameter values shown. The resulting time histories are shown in Fig. 9. They are seen to compare quite favorably with the experimental traces shown in Fig. 7a.

Finally, an analytical means for determing task difficulty using a structural model of the human pilot [7] was investigated. The approach was introduced in Ref. 2, but dealt soley with single-loop tracking tasks in that study. Figure 10 shows a simplified version of the structural model of the human pilot [2] . Following the lead of Smith [8] , it was shown in Ref. 2 that the RMS value of the signal u_m in the model of Fig. 10 correlated quite well with pilot opinion ratings of vehicle handling qualities when model parameters were selected which produced human operator transfer functions which matched those measured in experiment. It was hypothesized here that the method of Ref. 2 could be extended to multiloop tasks by considering the activity only in the inner-most loop of any multiloop task. For example, consider Y_{p_θ} for the completely manual configuration of Fig. 2. One can see from Fig. 10 that the RMS value of u_m is determined by the characteristics of the inner-loop command θ_c once the structural model parameters have been selected to provide a realistic Y_{p_θ}. Now the simplified structural model of Fig. 10 is parameterized by K_e and $K_{\dot{m}}$. However, for K/s controlled element dynamics, Fig. 10 indicates

$$u_m = (sK_{\dot{m}}/(s/\omega_c + 1))\theta_c$$

Thus, the effect of manual outer-loop closures in determining u_m is contained in the characteristics of θ_c.

Thus, using the nominal bandwidths of Eqn. (2), the RMS value of u_m can be determined in terms of the model parameter $K_{\dot{m}}$ for each automation level using the off-line computer simulation. The fact that the inner-most manual closure for any automation level always (except the position command) involves K/s dynamics and the control sensitivities have been optimized for each closure, leads to the final assumption that, in terms of the model, $K_{\dot{m}}$ can be considered invariant across all configurations.

The filled symbols shows the RMS u_m values obtained from the off-line simulation for each automation level, except the position command, in which K/s open-loop dynamics were not in evidence. In generating the RMS values of u_m (σ_{u_m}), the subject-generated position command was used in place of the actual task position command as discussed previously. To model the effects of noisy observations, broadband noise with an RMS value of 10 ft was injected in parallel with the position command. The noise was removed in modeling the human using the flight director since the single, compensatory closure would involve minimal observation noise as compared to the other closures.

DISCUSSION

Control strategy and automation level

The control strategy adopted by the subjects for each automation level can best be interpreted in terms of the resulting vehicle velocity time histories in Fig. 7. As the figure indicates, in configurations where preview information was available (all but the flight director) the velocity responses appear as a series of relatively uniform alternating pulses. With the outer position loop open in Fig. 2, the effective open-loop dynamics are approximately 1/s in the frequency region around ω_{c_u}. McRuer, et al, [9] have shown that a constrained time-optimal step-response control input to a K/s system under manual control is a rectangular pulse. The duration of the pulse was shown in 11 to be a physical constraint in manual control problems. In the simple single-loop experiments of [9] , the pulse duration was related to the duration of a "force program", i.e., the minimum time possible for the human neuromuscular system to generate an accurate pulsive control motion with an ideal manipulator. This concept can be adopted here and the duration of the velocity pulse is seen to be approximately 3 to 4 times the reciprocal of the pertinent loop crossover frequency, ω_{c_u}.

It must be emphasized again that the time histories evident in Figs. 7a - 7d cannot be adequately explained via Fig. 2 using the step position command x_c, only Fig. 7e, the flight director, can. This means that the available preview information has led to the generation of time optimal behavior on the part of the human, regardless of the automation level. As Fig. 4 indicates, position performance was also nearly independent of automation level when preview information was available.

Control movement analysis

The failure of the control movement analysis in following the subjective rating trends for the flight director can be traced to the fact that,in using the director, all the subjects adopted a very aggressive control strategy. This was attributed to the fact that the subjects were aware of the rather sluggish response of the flight director configuration relative to the other configurations where preview was available. The subjects tried to null director errors almost instantly by using pulsive control inputs. Although this strategy did not seem to detract from their subjective estimates of control difficulty, it certainly would effect the control movement analysis and can explain the flight director results of Fig. 6 as compared to Fig. 5.

Analytical task difficulty measure

The extension of the single-loop theory for interpreting the manner in which the human quantifies his subjective opinion of task difficulty to multiloop tasks appears feasible. The extension implies that task difficulty is determined by the activity in the inner-most loop being closed by the human regardless of automation level. Outer-loop effects, of course, influence the subjective estimates through the characteristics of the command signal to the inner-most loop.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Rouse, W. B., "Human-Computer Interaction in the Control of Dynamic Systems," Computing Surveys, Vol. 13, No. 1, March 1981, pp. 71-99.

[2] Hess, R. A., and Sunyoto, I., "Toward a Unifying Theory for Aircraft Handling Qualities," AIAA Paper No. 84-0236, 22nd Aerospace Sciences Meeting, Jan. 1984.

[3] McRuer, D. T., and Krendel, E., "Mathematical Models of Human Pilot Behavior," AGARDograph No. 188, 1974.

[4] Heffley, R. K., "A Pilot-in-the-Loop Analysis of Several Kinds of Helicopter Acceleration/Deceleration Maneuvers," Proceedings of a Specialists Meeting on Helicopter Handling Qualities, NASA Ames Research Center, April, 1982 NASA Conf. Pub. 2219, pp. 221-231

[5] Hess, R. A., "Nonadjectival Rating Scales in Human Response Experiments," Human Factors, Vol. 15, No. 3, 1973, pp. 275-280.

[6] Weirwille, W. W., and Connor, S. A., "The Sensitivity of Twenty Measures of Pilot Mental Workload in a Simulated ILS Task," Proceedings of the Eighteenth Annual Conference on Manual Control, June, 1982, pp. 150-162.

[7] Hess, R. A., "A Structural Model of the Adaptive Human Pilot," Journal of Guidance and Control, Vol. 3, No. 5, Sept.-Oct. 1980, pp. 416-423.

[8] Smith, R. H., "A Theory for Handling Qualities With Application to MIL-F-8785B," AFFDL-TR-75-119, 1976.

[9] McRuer, D. T., et al, "New Approaches to Human Pilot/Vehicle Dynamic Analysis," AFFDL-TR-67-150, 1968.

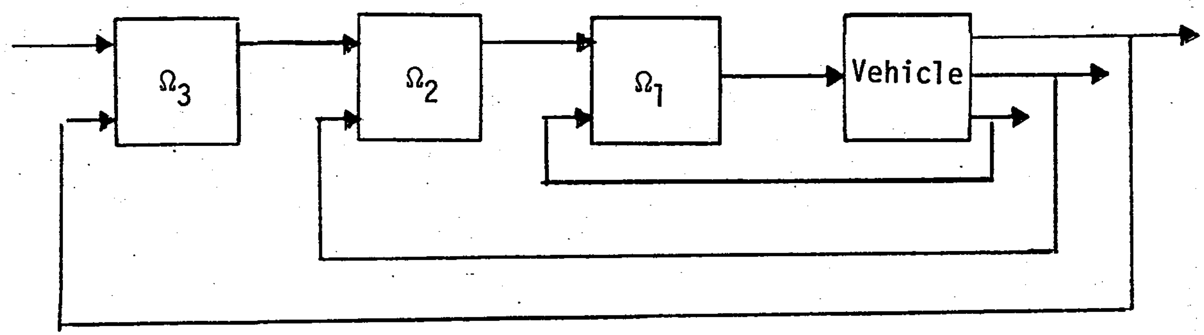
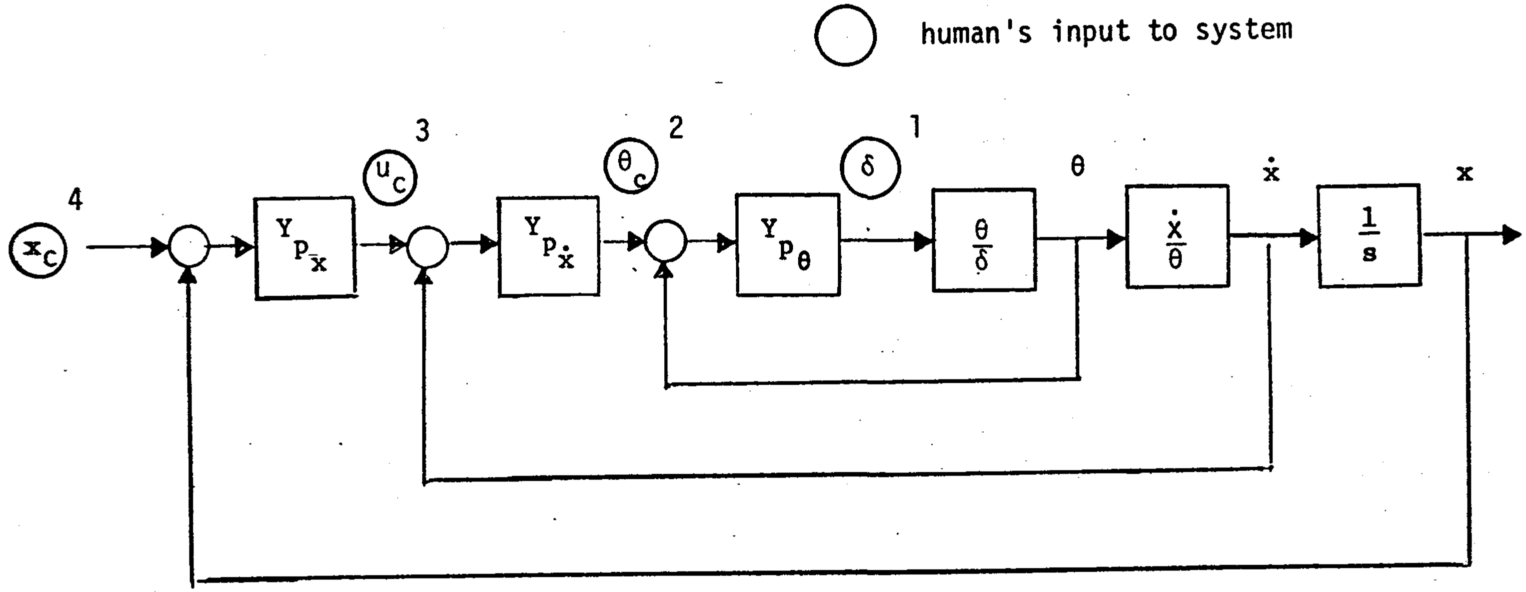


Figure 1. The general structure of dynamic systems



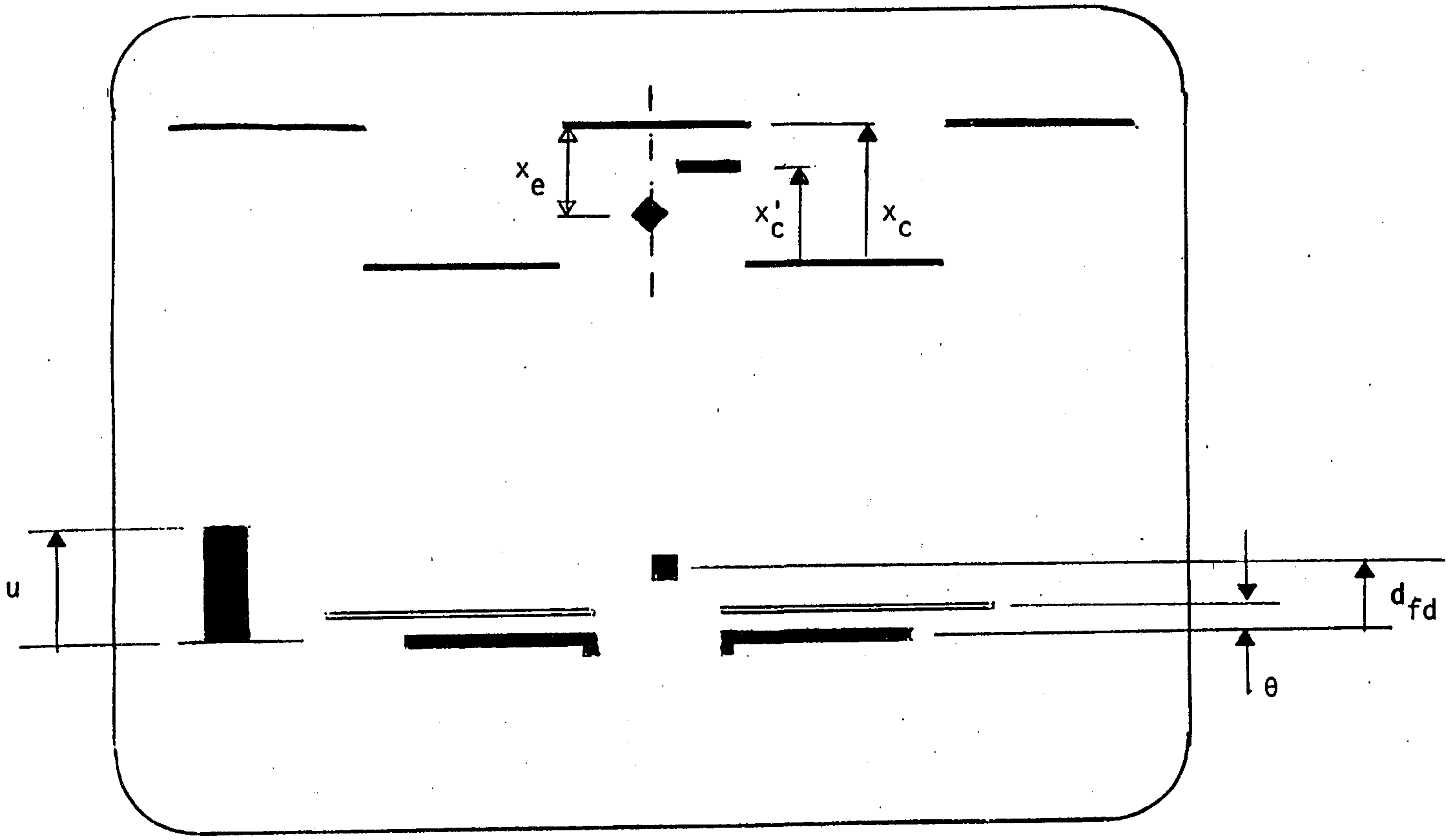
1 = human control input for rate-command system

2 = " " " " attitude-command system

3 = " " " " velocity-command system

4 = " " " " position-command system

Figure 2. The stereotype multiloop system - hypothesized pilot loop closures for a longitudinal VTOL hover task



u = vehicle velocity

θ = pitch attitude

d_{fd} = flight director command

x_c = actual task position command

x'_c = subject-generated position command

x_e = position error

Figure 3. Display format for longitudinal hover experiment

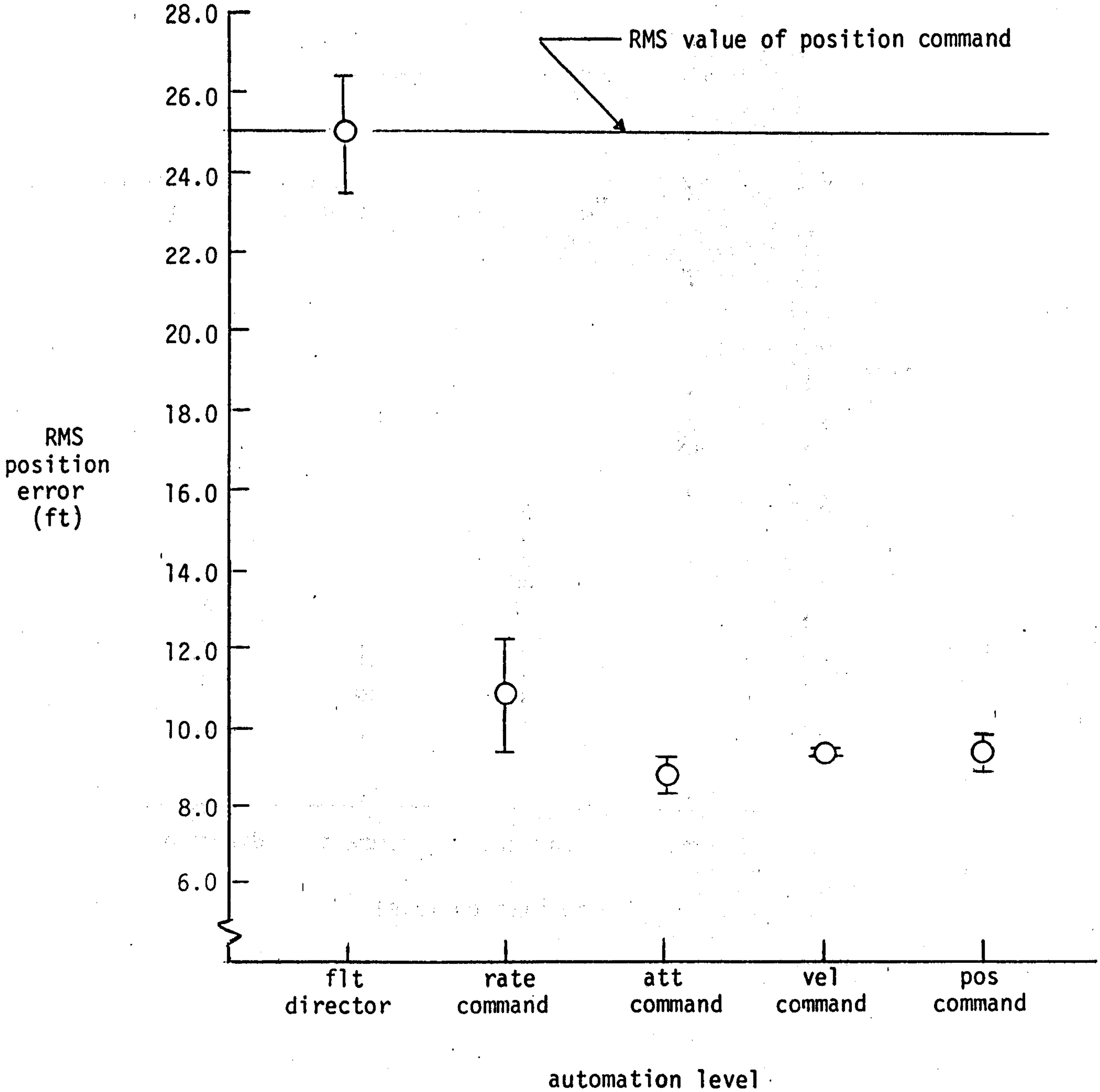


Figure 4. RMS position performance for one subject for various automation levels. Average of 5 runs.

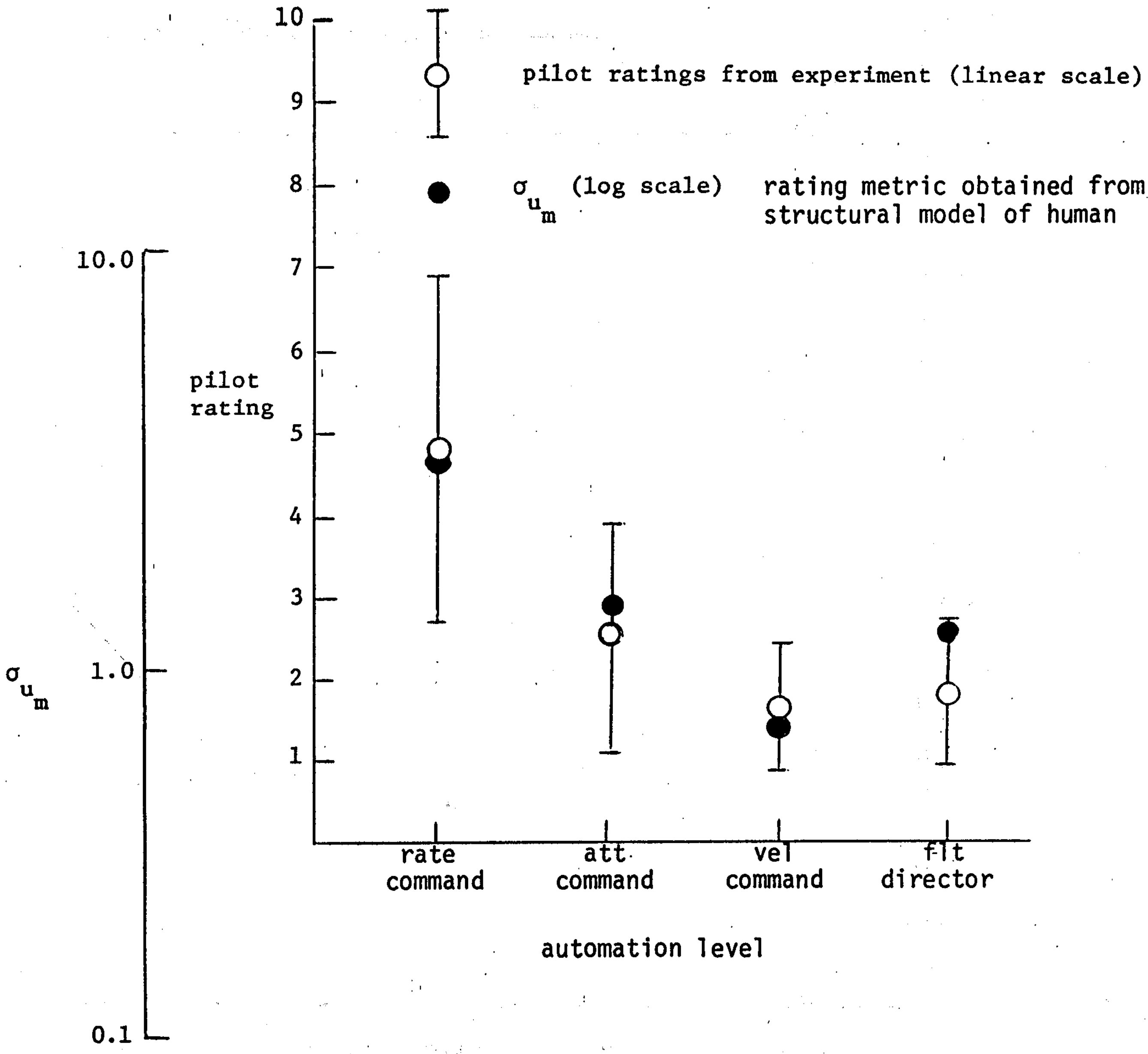


Figure 5. Comparison of subjective task-difficulty ratings with model-based metric

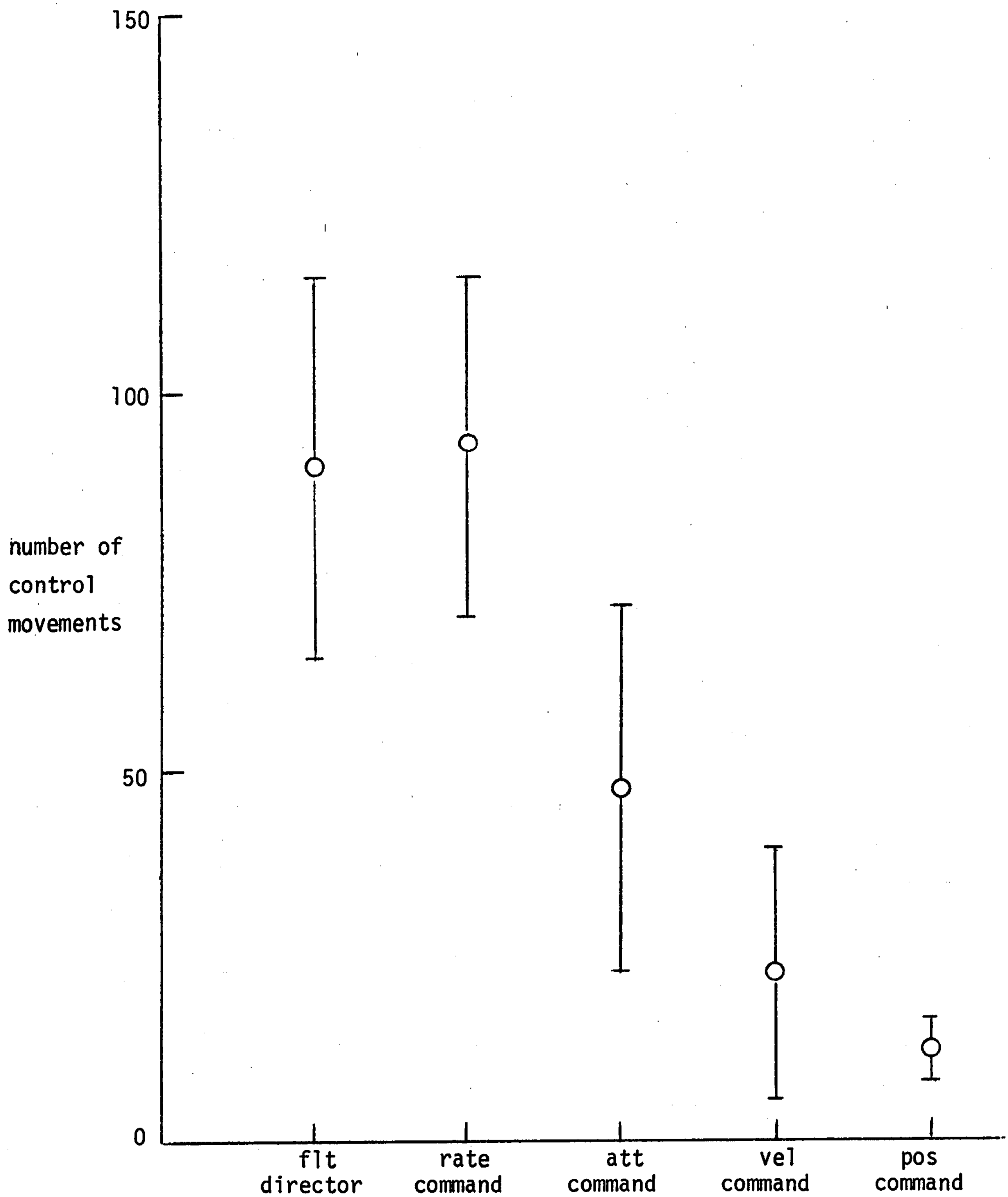


Figure 6. Control movements analysis

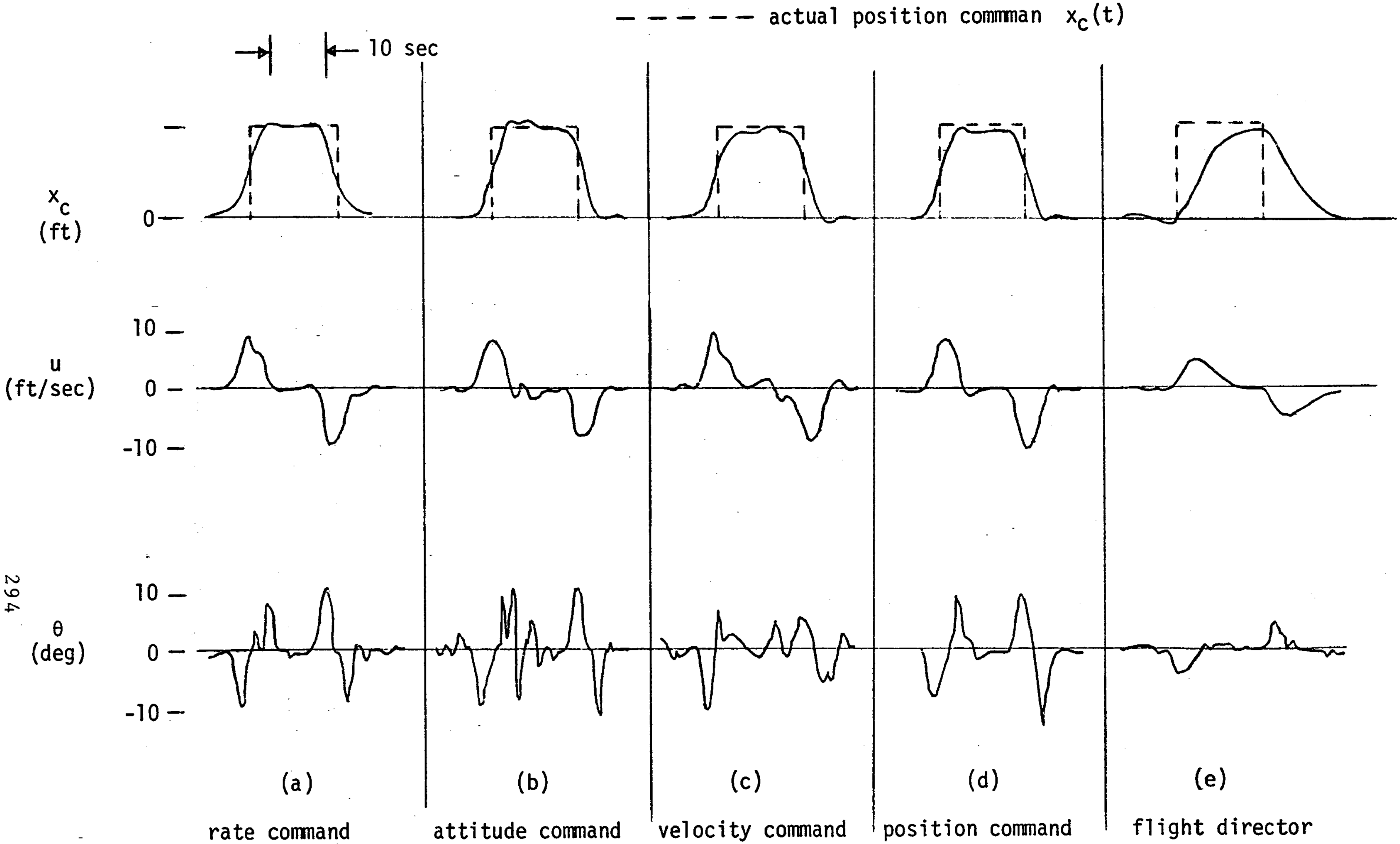


Figure 7. Typical time responses for one subject

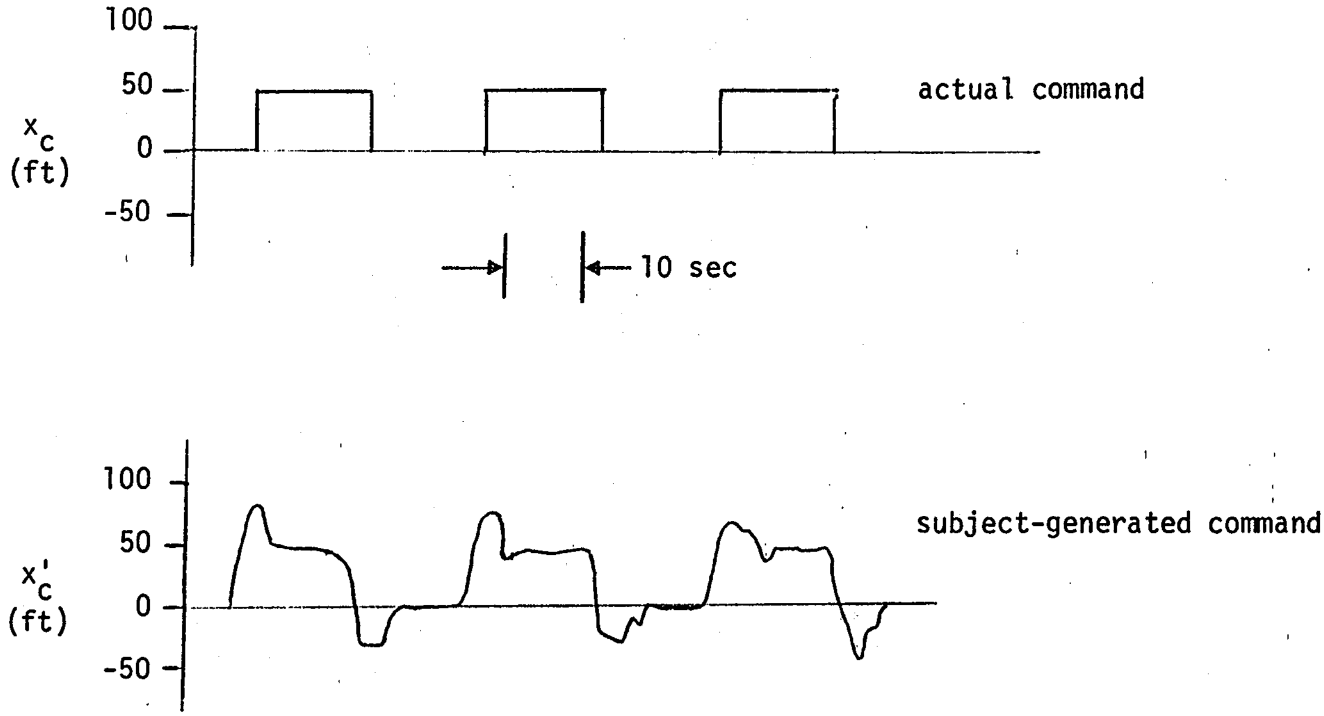


Figure 8. Comparison of actual position command with subject-generated command

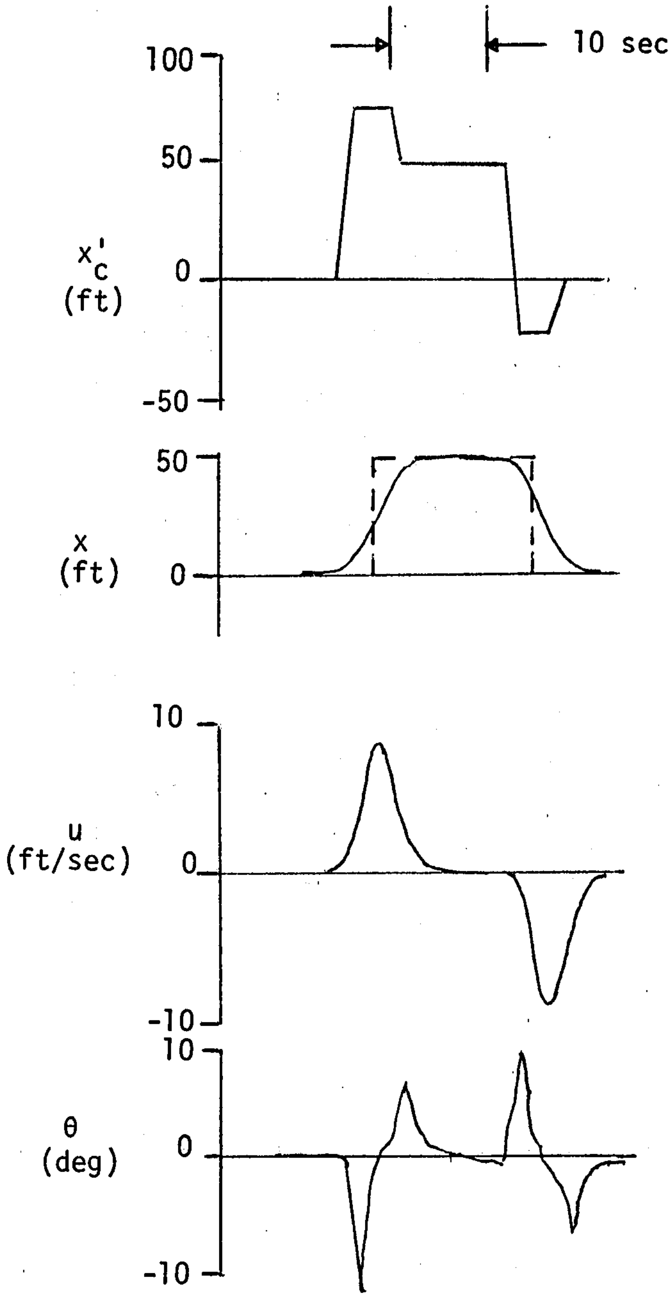


Figure 9. Model generated time responses

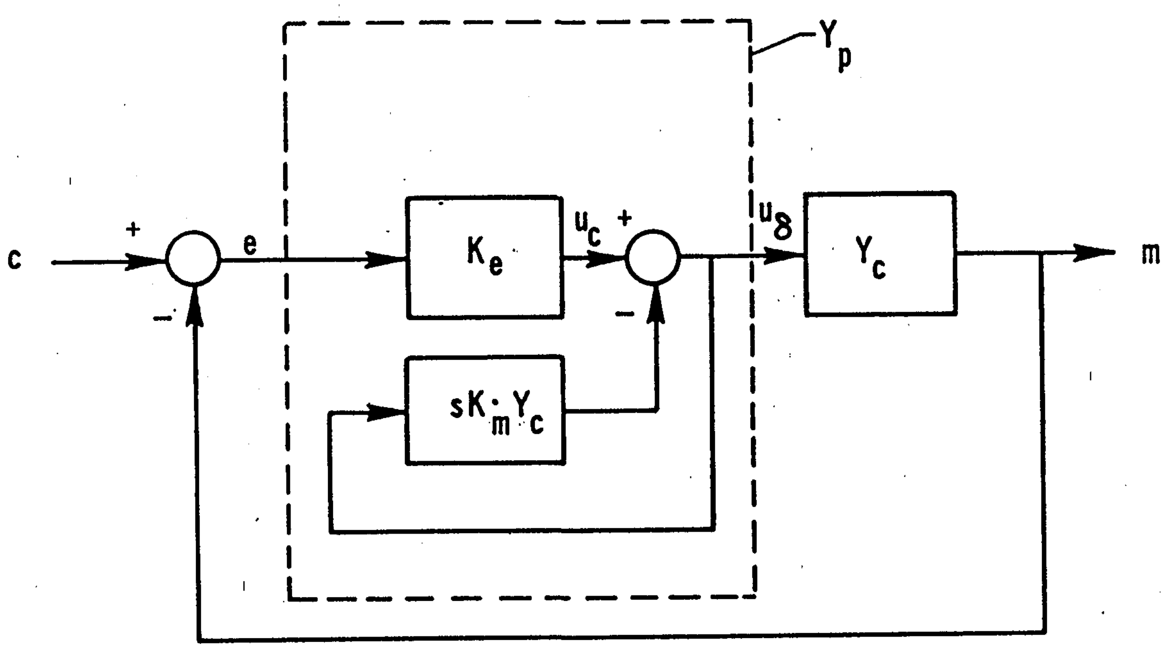


Figure 10. A simplified structural model of the human controller for single-loop tasks.