SOME CRITERIA FOR TELEOPERATORS AND VIRTUAL ENVIRONMENTS FROM EXPERIENCES WITH VEHICLE/OPERATOR SIMULATION

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Over 30 years of experience in the simulation, modeling and analysis of man-machine control systems has resulted in a variety of rules-of-thumb and some quantitative criteria for assuring valid simulation of "real-world" situations and likely users. It is hoped that these criteria, which apply directly to teleoperations (i.e., no communication delays; operator-in-the-loop; no "smart-robot" delegation), will be useful for designing better telerobots and in simulating telerobotic controls and virtual environments.

First, some definitions are given: "Valid simulation" is defined as that producing the same operator behavior, performance and mental workload as the real-world case. "Delay artifact" is the (measured) sum of all throughput delays from: sensing, computing, pipeline and display generation. "Kinetosis" is the vertigo and malaise from conflicts among visual, vestibular and proprioceptive motion cues. "Mental workload" is the operator's evaluation of his attentional-load margin while performing adequately in a specified task context.

A review is given of a wide range of simulations in which operator steering control of a vehicle is involved and the: dominant-cues, closed-loop bandwidth, measured operator effective time-delay, and ratio of bandwidth-to-inverse delay, are summarized. For well designed and low mental workload conditions, this ratio is well under 1.0, as control theory would dictate. However, for important human tasks like fast locomotion, the ratio approaches 1.0 (limited by the inverse delay limit of about 8 rad/sec), and the mental workload becomes critical. These imply requirements that the eyeball stabilization and pursuit subsystems have higher bandwidth. More importantly, it dictates that any simulation delay artifact must be less than about 1/4 of the effective operator delay in a given task, i.e., less than about .04 seconds delay artifact for locomotion simulation.

A correlation of kinetosis (simulator-sickness) with dynamic scene field-of-view (FOV) is shown. It has been found that, to avoid kinetosis, the FOV should span less lateral view than a curve of about 1.10 Gy would cover at real-world speeds (typically, less than 60 degrees). Other requirements include: framing of scene "streamers" and avoidance of perceivable image jitter or "strobing."

The visual resolution of a virtual environment should allow reading a newspaper subheadlines at arms length. High Definition Television (HDTV) would pass this test.

The use of moving base simulators to improve the validity of locomotion teleoperations is discussed, and data are shown to support the following recommendations. Linear motion bases are not needed if the real-world task entails less than about 1.1 Gy of transverse acceleration. If the rms Gy is greater, it is more important to maintain correct motion-cue phasing (<30 degree disparity) than

amplitude, which can be cut to about 1/5 the actual levels. Rotary motion rates are sensed and used as "rotary motion dampers" when the real-world task is regulation against inertial motion disturbances (as in running), but are ignored when the task involves pursuit of a maneuvering target. Details are discussed in the presentation.

Some rules-of-thumb for good "feel-system" simulation, such as for control manipulanda are given. Their vernacular version dictates that "good" simulation of a:

- **zero inertia and force-free control** should "feel like a stick of balsa wood" (negligible friction, jerk or jitter)

- **hard stop** should "feel like a brick wall" (no creep or sponginess)

- **coulomb friction** should "feel like sliding a refrigerator magnet" (remain in place; no creep, bounce or jitter)

- **centering detent** should "yield an audible "klunk" when traversed" (no lag or sponginess)

Try these on your favorite manipulandum!

Finally, simulation tests of teleoperators and virtual environments should include three types of measures: system performance, operator (or robot) "behavior" (e.g., describing functions, etc.), and mental workload evaluations. The criteria for adequate mental workload measures are that they be:

1. Relevant	-	to mental workload, *per se*
2. Sensitive	-	monotonic correlation with workload
	-	insensitive to irrelevant variables
	-	high test power (covariance/residual)
3. Concordant	-	ubiquitous trends in target population
4. Reliable	-	proven test: retest repeatability
	-	proven norms and statistics
5. Convenient	-	easy to administer and learn
	-	portable
	-	low cost for adequate level of reliable result

Properly designed subjective ratings usually fare better than such measures as evoked response potentials! Examples of the foregoing approach are given, in optimizing motion washouts.

If your teleoperator or virtual environment simulation can pass these rule-of-thumb tests, then you can be fairly sure that it will provide results which can stand the final test of real-world validation, form a proper data base for scientific modeling and engineering design, and be liked by its users.

CONTROL BW AND H.Q. DELAYS ARE RELATED

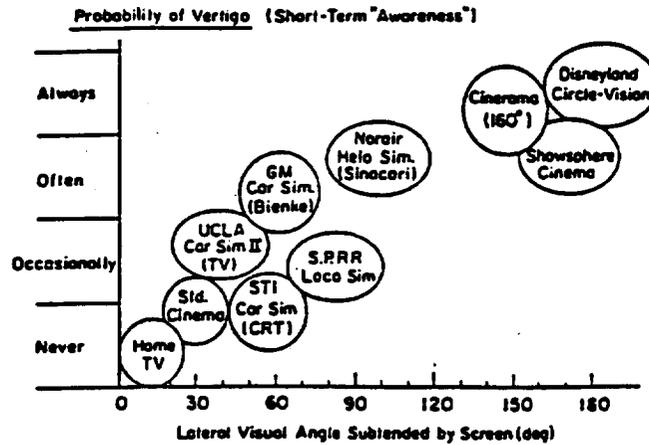| SIMULATION (Example)	DOMINANT CUES			CLOSED-LOOP BANDWIDTH BW (r/s)	TYPICAL OPERATOR DELAY τ(sec)	$\dfrac{BW}{\tau^{-1}}$
	VISUAL	MOTION	FEEL			
Ship Conning (SES-2000)	√	Disturb	–	.01–.10	2–5	.20
Blimp mooring (S-500)	√	–	–	.3	.5	.15
Manual Booster Control (Saturn V)	√	Disturb	Disturb	1.5	.3	.45
Transport Aircraft (Boeing 707)	√	Some	√	2.0	.25	.5
Fighter Aircraft (F-16)	√	√	√	4.0+	.15–.22	.7
Automobiles (Honda)	√	√	√	4.0+	.25	.8
Bicycle (slow) (Recumbent Bike)	√	√	√	6.0	.15	.9
Cursor Aiming (Critical Instability Task)	√	–	–	6.0–8.0 (limit)	.12–.20	1.0
Eye - Pursuit Loop	√	–	–	10	.06	.6
Eye - Vestibulo-ocular	?	√	?	30+	.02	.6

IMPLICATIONS – VISUAL DELAYS

- Optimized control tasks have $BW/\tau^{-1} \ll 1.0$

- Human will adapt τ_{eff} to $\approx 1/5$ BW, down to $\tau \approx .20$ sec

- For high BW tasks: $BW/\tau^{-1} \approx 1.0$ and $\tau_{min} > .16$ sec

- Control theory shows that any simulation delay artifacts must be $\ll .20$ sec to provide "valid" simulation

Criterion 1

- ∴ "Valid" simulation requires delay artifacts be $\ll .20$ sec:

    <.02 sec (60Hz) = Excellent; <.04 sec = Good; >.10 sec = Invalid

FIELD OF VIEW VS. KINETOSIS
Fixed-Base Vertigo vs. Field of View

Probability of Vertigo (Short-Term "Awareness")

Lateral Visual Angle Subtended by Screen (deg)

<u>Implications:</u> For wide FOV use "impoverished scene"

Criterion 2:   Keep FOV to cover less lateral view than a curve of $\pm.10\ G_y$ would cover at real-world speeds

<u>Other factors:</u>

- More parafoveal details ⟶ worse conflict

- Proper framing of parafoveal streamers is important

VISUAL UPDATE AND RESOLUTION OF DISPLAYS

Criterion
- For "inner loop" control of path rate and curvature, "streamers" from scene microtexture should not jerk or strobe backward.
  (≈ 20-60 frames/sec update)

Criterion
- For "outer loop" guidance and navigation must be able to perceive and understand cues at ≈ 3-5 sec ahead of vehicle
  Implies ≈ 2 min-arc of resolution for signs, potholes, targets (e.g., HDTV)
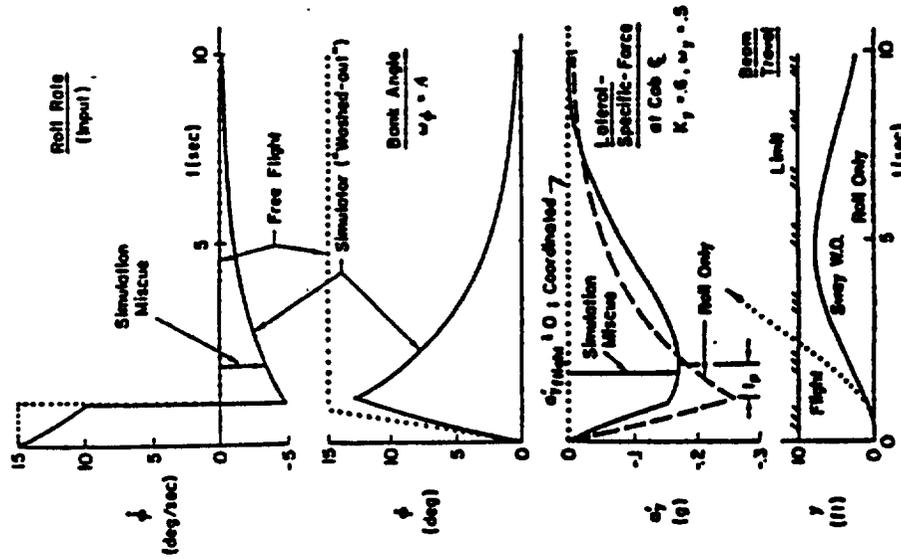
Criterion
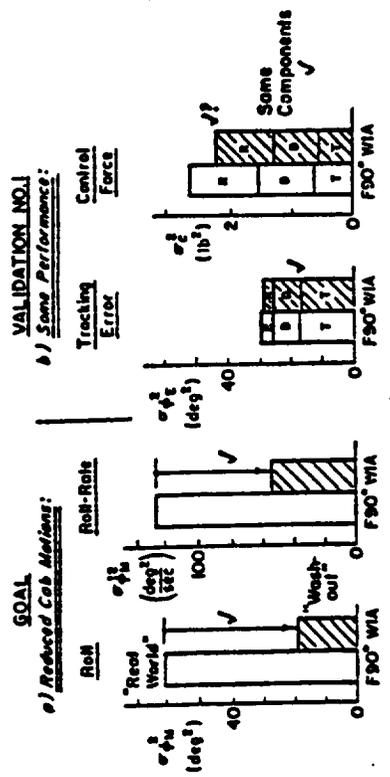- For Virtual Environment should be able to read a newspaper at arm's length. (Subheadlines = OK) (e.g., HDTV)
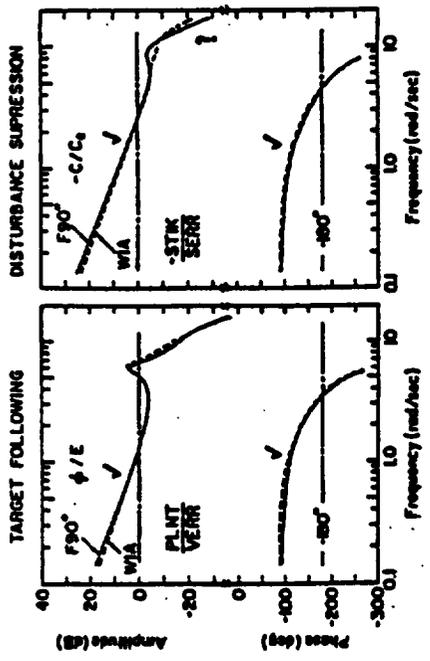
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VERIFICATION OF VALID SIMULATION

OPTIMUM WASHOUT (Attenuated First-order)

GOAL

VALIDATION NO.1

a) *Reduced Cab Motions:*

b) *Same Performance:*

Roll

Roll-Rate

Tracking Error

Control Force

Some Components ✓

"Real World"

"Wash out"

✓

$\sigma_{\phi_M}^2$ (deg²)

$\sigma_{\dot\phi_M}^2$ (deg²/sec²)

$\sigma_{\phi_e}^2$ (deg²)

σ_{c}^2 (lb²)

F90° W1A

F90° W1A

F90° W1A

F90° W1A

VALIDATION NO. 2 c) *Same Behavior:* (open-loop descr./cn.)

TARGET FOLLOWING

DISTURBANCE SUPPRESSION

ϕ/E

$-C/C_a$

F90°

F90°

W1A

W1A

PLNT VERR

-STK SERR

-180°

-180°

Amplitude (dB)

Phase (deg)

Frequency (rad/sec)

Frequency (rad/sec)

VALIDATION NO. 3: *Same Subjective Evaluation:*

Cooper-Harper Ratings: F-90°: 4   W1A: 5

MOTION CUE ARTIFACTS

TURN ENTRY; FLIGHT VS. SIMULATOR

Roll Rate (Input)

Free Flight

Simulation Mfscue

$\dot\phi$ (deg/sec)

t (sec)

Bank Angle $\omega_\phi \cdot A$

Simulator ("Washed-out")

ϕ (deg)

Lateral-Specific-Force at Cab ℄ $K, \cdot \delta, \omega_\rho \cdot .5$

σ_{input} '0 ¦ Coordinated'

Simulation Mfscue

Roll Only

$-U_0 \dot p$

a_y^c (g)

Beam Trend

Limit

Sway W.O.

Roll Only

Flight

y (ft)

t (sec)

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COMPARISON OF OPTIMUM SWAY WASHOUT VS. ROLL ONLY

MEDIUM SWAY WASHOUT VS. ROLL ONLY

GOAL: a) CAB MOTIONS "SIMILAR"

VALIDITY NO.1 b) PERFORMANCE "SAME"

SPECIFIC FORCE — "Marginally Acceptable"

ROLL RATE — "Same"

TRAVEL (Benefit of Roll Only)

TRACKING ERROR
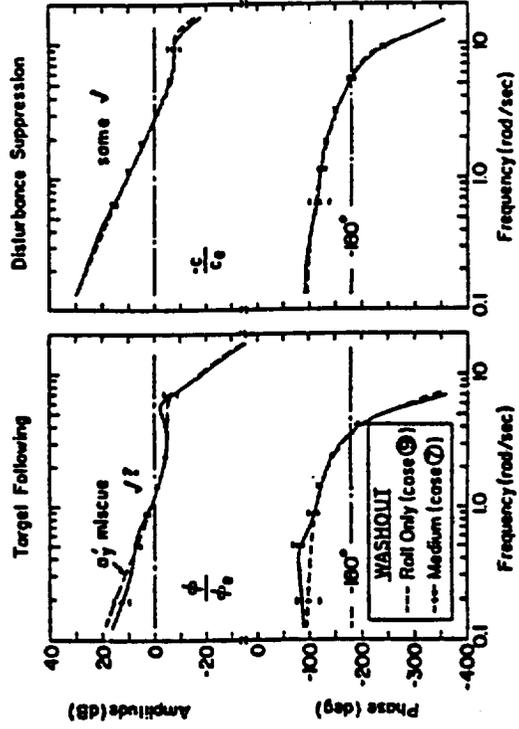
σ_{a_y} (g) — .1 .2 .4 .6 .8

σ_{ϕ} $\left(\frac{deg}{sec}\right)$ — 2 4 6 8 10

σ_y (ft) — 1 2 3 4 5

σ_{ϕ_e} (deg) — 1 2 3 4 5

Sway Washout "∞" — Med
Roll Only $K_y = .6$ $\omega_y = .5$
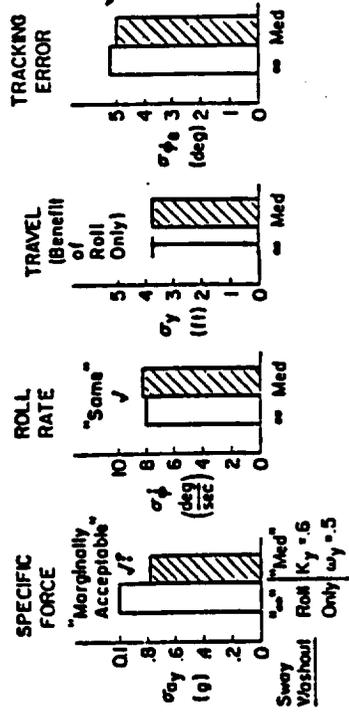
c) BEHAVIOR "SAME"   VALIDITY NO.2

Target Following

Disturbance Suppression

a'_y miscue

some $\checkmark$

$\frac{\phi}{\phi_e}$

$\frac{c}{c_e}$

$-180°$

WASHOUT
--- Roll Only (case ⑨)
-·- Medium (case ⑦)

Amplitude (dB): 40, 20, 0, -20
Phase (deg): 0, -100, -200, -300, -400

Frequency (rad/sec): 0.1, 1.0, 10

SWAY WASHOUT PARAMETERS VS. COMMENTS

Sway Washout Frequency, ω_y (rad/sec): 0, .2, .4, .6, .8, 1.0 — Roll Only

High Frequency Gain, K_y: No Sway Motion, Attenuation .2, .4, .6, .8, 1.0 Full Motion

≈ Roll-only; small Δt_p, $a_y \approx g\phi$

"THE LEANS"

UNDESIRABLE a_y motion-cues highly distorted

ACCEPTABLE

"DELAYED SIDE-FORCE" trans-threshold a'_y large Δt_p

Travel Limits Exceeded

FULLY COORDINATED Free-Flight
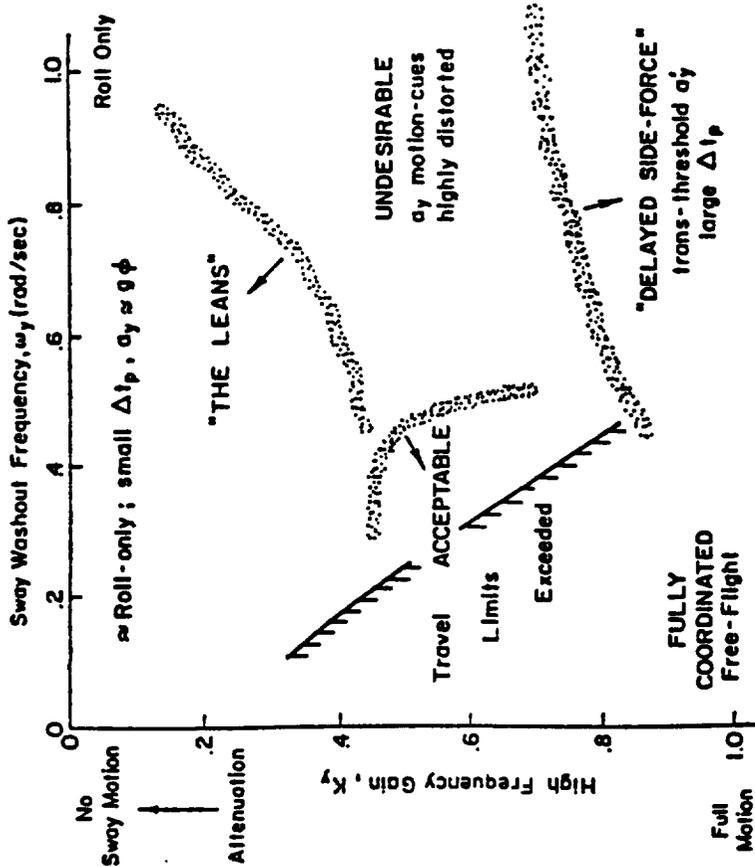
Jex, Henry R., Raymond E. Magdaleno, Wayne F. Jewell, et al., Effects on Target Tracking of Motion Simulator Drive-Logic Filters, AMRL-TR-80-134, August 1981.

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