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**OMV Man/System Simulation Integration:
A Preliminary Analysis and Recommendation**

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OMV Man/System Simulation Integration:
A Preliminary Analysis and Recommendation

Introduction

The OMV presents a series of challenges to the human operator. Some are unique to the OMV system itself, and are largely due to remote control versus control from the cockpit. For example, the vestibular cues of vehicular motion are absent. Moreover, the operator must rely on a telemetered visual image from cameras on the OMV for tracking and acquiring the target, an image which only approximates that which an onboard pilot would see. Further complications are added if frame dropout and time delay are present. Other challenges are not necessarily unique to the OMV, but are characteristic of many man-machine space flight systems. For example, operating the vehicle in zero gravity removes certain 1-g perturbations but adds others. Also, the target vehicle may be unstable, that is, rotating or wobbling on either a regular or an irregular axis. Acquiring an unstable target is difficult under the best of circumstances; while airplane pilots accomplish carrier landing through repetitive trials and overlearning, OMV missions will be nonrepetitive. All of these challenges affect the operator's ability to perform his portion of the mission, and could lead to human error which might jeopardize the vehicle, the mission or both. In a situation such as presented by OMV with its unique problems and complications, it is imperative to make every effort to design the controls and displays to facilitate the operator's task. A mission failure might ostensibly suggest human error, whereas in

reality, the failure may be attributable to situation-caused error from poorly designed controls/displays and/or invalid simulation practice. Facilitative control/display dynamics can be evolved through careful and thorough simulation experiments. A comprehensive experimental program systematically examining the relevant control/display parameters can provide the converging operations necessary to derive a set of control/display parameters which facilitates the operator's performance and provides him with the tools to be an integral and effective component of the OMV man-machine system.

The experimental program should address the perceptual, mediational and motor dimensions of an operator's performance. With this in mind, a literature review with relevant design considerations has been initiated, and a comprehensive outline of control/display parameters has been developed. Out of this, a series of questions not answered in the literature has been derived which can be converted into experimental protocols for the simulation program.

Microcomputing and display technological advances have made feasible the use of pictorial flight displays which have proven to facilitate a pilot's performance in airplanes. A major task of the airplane pilot as well as the OMV operator is prediction, i.e. anticipating the effect of a controlled action. Certain display principles have proved to enhance the pilot's ability to predict (Roscoe, et. al., 1981). A brief examination of some of these principles in relationship to OMV may be useful.

MAGNIFICATION

Pictorial display magnification has proved to enhance prediction performance. Roscoe (1950) showed that the apparent distance of targets as seen on a flat screen display is greater than the perceived distance to the target when viewed directly. Vertical distance judgments were achieved using a magnification factor of between 1.2 and 1.29. Magnifying a display increases the sizes of the movements of the display markers, and thus makes the errors look larger.

As currently configured, the OMV display is a target referenced compensatory display. In this type display, the target is stationary and the vehicle (or in the case of the OMV simulation the camera is stationary) moves toward the target. In the target motion simulator it appears as if the vehicle moves toward the target. With this type of display moderate magnification has been found to be reliably better than too much or too little magnification (Poulton, 1974). Precise amplitudes of displayed movements of track in inches must be determined through experimentation.

Information Integration

The most significant mediational or information processing task of an operator is the integration of information from different sources. The OMV currently displays information on certain of the hierarchically related flight control loops (position, range and range rate). Utilizing these data requires the operator to perform separate interpretation, transformation and integration prior to selection of control responses.

Presently, these data are presented in parametric displays which are not well suited for rapid qualitative interpretation of the state of the system required in vehicle control (McCormick, 1976). To the extent that the data dimensions are integral, they can be combined into an integral display.

A variety of experiments have demonstrated the advantage of object integrality in information integration in abstract pattern classification tasks (Jacob, Egeth, & Bevan, 1976, Goldsmith and Schvanveldt, 1984); and in process control simulations (with a triangle display (Carswell and Wichens, in press). This advantage also held using pentagon displays (Jones and Wickens, 1986) and a rectangle display in a command and control scenario (Wichens and Scott, 1983). A parametric evaluation of several integral configurations could enhance the operator's performance.

Predictor Displays

As noted earlier the primary operator task is the prediction of future effects of present control inputs. Prediction displays have been used to assist the pilot. Predictor algorithms provide the pilot with estimated successive future states of the vehicle based on current states and control inputs for comparison with desired systems states. Typically these are all integrated in a single display for direct comparison by the pilot. Studies using predictor displays have shown improved performance in simulated lunar landings (Fargel and Ulbrich, 1963) and have demonstrated a reduction in performance variability between subjects (Warner, 1968).

The importance of anticipation and timing in performing a complex control task cannot be overemphasized. The basic components of motor skills are spatial (what movement to make) and temporal (when to make the movement). The principle variable affecting timing is the ability of the operator to anticipate future stimulus events. Skilled motor performance has been enhanced through perceptual anticipation by means of which a subject learns repeatable aspects of a stimulus event and responds accordingly (Poulton, 1950). As stated earlier, OMV flights will, in all likelihood, be nonrepetitious, depriving the operator of overlearned perceptual anticipation typical of other complex motor tasks (e.g. aircraft landing).

Research supporting the advantages of prediction is pervasive (Simon, Slocum, Hopkins, and Roscoe, 1956; Simon and Roscoe, 1956; Bauerschmidt and Roscoe, 1960; Besco, 1964; Kelley, Mitchell and Strudwick, 1964; Sweeney, Todd, and Heaton, 1965; Bernotat and Widlok, 1966; Kreifeldt and Wempe, 1973; Smith, Pence, Queen, and Wulfeck, 1974; Jensen, 1979; and Roscoe and Jensen, in press). Furthermore, NASA Langley Research Center supporting the Terminal Configured Vehicle program is expected to produce an operationally qualified pictorial predictor display (Roscoe and Jensen, in press).

A procedure for predicting which would appear to be particularly suitable to the OMV would be a target-referenced compensatory display with a target predictor. In this format (see Figure 1), V and v move. When a control input is made, the operator will see a prompt shift of the predictor symbol (a small v) that alters this prediction. A systematic and thorough

experimental program would also require examining the appropriate mix of predictions between V and T. Predictions can be separated into portions and applied to the vehicle and target. This parameter may vary between 0 and 100% on the vehicle symbol and the remainder applied to the target predictor symbol. For example, the predictor function may be 100% applied to the target (see Figure 2).

If the target is unstable and rotating or wobbling, there might be a distinct advantage in having the predicting divided between the target and the unstable vehicle (see Figure 3).

In this manner the predictor is partitioned according to some optimal fraction resulting in optimal performance.

In conclusion, magnification, integrated displays and predictor displays are but a few significant issues for serious experimental examination in the OMV program. The recent proliferation in avionics technology of low-cost, light weight and highly reliable computing and display devices has made feasible the implementation of display principles heretofore considered impractical. Frequently, simulation questions have been posed in terms of "Can the operator perform the docking maneuver under certain adverse conditions using the current control/display configuration?" Obviously, these questions have to be addressed and answered. However, today it is feasible and totally reasonable to utilize current avionics technology in such a way as to have a control/display configuration that not only maximizes but enhances the operator's performance. It is reasonable to expect man with the benefit of a well-engineered

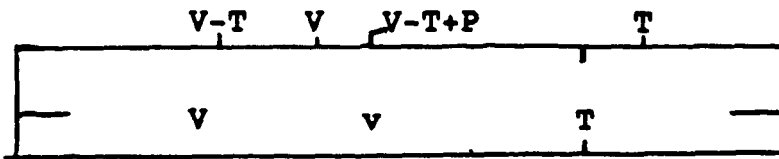


Figure 1. Target-referenced compensatory display with vehicle predictor (V and v move).

V - Vehicle, T - Target, v - Vehicle predictor

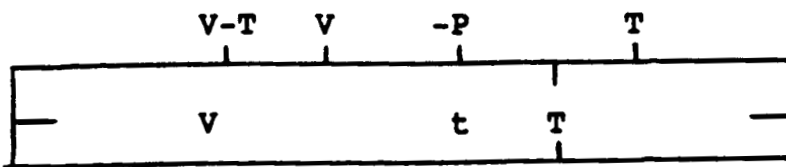


Figure 2. Target-referenced compensatory display with target predictor (V and t move).

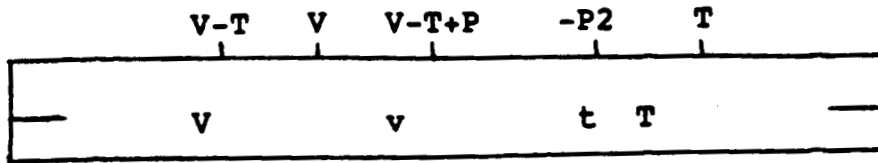


Figure 3. Predicting applied to target referenced compensatory display with target and vehicle predictor (V , v and t move).

control and display to consistently perform vehicle docking scenarios previously considered impossible.

In addition to the display issues discussed above, a comprehensive list of additional experimental test plan parameters can be found in Table 1.

Current OMV Control/Display Configuration

A systematic experimental program includes consideration of and/or experimental evolution of these issues. Data presented subjects in the control and display format currently used in OMV simulation may be seen in Table 2. Controls in the current configuration include two hand controllers, one for translation/acceleration and another for rotational control with the capacity for inputs in three axes: pitch, roll and yaw. Push button controls are available for selection of translation and rotational pulse as well as perimeter camera angle control (i.e. pan, tilt and zoom).

All data presented in the current display listed in Table 2 are digital with the exception of the three docking pins which change color from blue to green when in contact. The probability is low that the operator performing the docking task could perceive, interpret, and act on information presented in this manner. He would have to remember in which of the seven locations on the display screen the data are presented, the units in which the data are displayed (i.e. feet from target, angles, feet per second, etc.), and extrapolate what the data means in terms of his particular information requirement at that moment. Subjects have reported that in terms of performing the docking

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Table 1

Experimental Test Plan Parameters

OMV Work Console Parameters

Type of Operator: Experience level
Controller Requirements: Types, Modes, Parameters
Display Requirements: Types, Video parameters, Aids

OMV Vehicle Parameters

Camera: FOV, Location, Configuration
Thruster Parameters: Size, Impulse

OMV Mission Translation (Slewing) Parameters

Distance: Short range, Medium range, Long range
Payload: Placing in orbit/retrieving from orbit
Time Delays: Values
Frame Dropout

Target Acquisition Parameters

Visibility Conditions: Sun angle, Visibility around,
Attached payloads
Work Task Performed at Target
Attitude: Stable/Unstable, i.e. spinning, coning, tumbling

Table 2

Data Presented in Control and Display Format
Currently Used in OMV Simulations

Data Presented on Display:

Range - feet from target (digital)
Pan tilt target
Time into the mission
Range rate - feet per second translation
OMV attitude rates - roll, pitch and yaw
Docking pin contact
Fuel use

Data Presented on Console:

Range in feet in 3 axes, X, Y and Z
Range rate in feet in 3 axes, X, Y and Z
Local vertical
Local horizontal
Translation pulse - continuous, 100 milisec pulse, 200
milisec pulse •
Rotational pulse - continuous, 100 milisec pulse, 200
milisec pulse •
Perimeter camera angles - pan, tilt and zoom*

* Also incorporate push button selection controls.

task the most important digitally displayed information was OMV attitude rates of roll, pitch and yaw reported at present in degrees per second of rate of change (i.e. pitch + for up, - for down; yaw + for right, - for left; and roll + for right, - for left). This information is currently displayed in the center along the base of the display. The second most important digitally displayed information was judged to be range rate displayed in feet per second translation toward the target (negative values), or away from the target (positive values). This information is currently displayed to the left of the operator along the base of the display. The third most important digitally displayed information was opined to be range displayed in feet from the target and currently located along the top of the display to the left of the operator.

Display Recommendations for Existing Configuration

Several control/display principals might be immediately implemented to enhance the subjects' docking performance. In each case, the suggested changes could be compared with the present control/displays to determine if performance changes are sufficient to justify modifying the existing configuration. First, it is recommended that certain continuously displayed information be removed from the display. For example, fuel use and time into the mission could be displayed only if current rate of fuel usage or mission time suggested a potentially mission-threatening condition. The camera angle display could be removed but with the ability to have this information displayed if needed. Docking pins could be displayed in such a way that they

are located in the center of the screen and light up red when within the acceptable docking envelope. Range, Range Rate and OMV Attitude rates lend themselves well to the use of geometric integrated displays. Experimentation would be required to determine the optimal form to display and optimal location of the display on the screen. Range and Range Rate being correlated variables have the potential of being combined into a single display. In a complex perceptual task such as the OMV, the worth of this cue will be defined as a product of its reliability or trustfulness and its diagnosticity or relevance to the operator. To the extent that a geometric forms area is a commodity that can be perceived directly, then it will stand as an emergent feature directly supporting the operator's integration task. Pomerantz (1981) has characterized those emergent features as a property of the configuration of multiple dimensions of an object which simply does not exist when the dimensions are displayed independent of each other. The OMV attitude display could also be displayed in an integrated display. These recommendations would reduce the amount of information displayed to the operator on a continuous basis, combine two digital displays into one integrated display, and convert another digital display into an integrated display. These procedures should make the information more useful to the operator and remove potentially confusing and distracting information.

Controller Recommendations for Existing Configuration

With regard to the hand controllers, it may be possible to combine the functions of both controllers as currently used into

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Table 3

Experimental Program Recommendations

Experiment	I.	Display Configuration X Time Delays X Target Attitude
Experiment	II.	Predictor Displays X Time Delays X Target Attitude
Experiment	III.	Magnified Displays X Time Delays X Target Attitude
Experiment	IV.	Type of Operator X Time Delays X Target Attitude
Experiment	V.	Hand Controller Type X Time Delays X Target Attitude
Experiment	VI.	Mission Scenario X Time Delays X Target Attitude
Experiment	VII.	Camera Configuration X Time Delays X Target Attitude
Experiment	VIII.	OMV Vehicle Anamoly Analysis X Time Delay X Target Attitude

a single hand controller. Acceleration or translation could be controlled by forward, backward, right, left movement. Rotational commands could be performed by tilting the hand controller forward or backward (pitch), tilting the hand controller left to right (yaw), or twisting the hand controller right or left (roll). This would permit the operator to use his left hand to control the camera (pan/tilt/zoom) for the final precision docking maneuvers. The left hand could also be used for other switching as needed. A foot controller could be used to activate or deactivate the acceleration function in the final stages of docking.

Experimental Protocol Recommendations

Table 3 presents a series of experimental questions which are designed to systematically test the relevant control/display parameters. Each set of control/display parameters is tested with time delays and variations in target attitude, both of which constitute graduation of task difficulty. As the experimental program progresses, if no significant differences are found among certain time delays and/or among certain target attitudes, then the number of these parametric values can be reduced and previous data pooled. Experiment I has been elaborated into a protocol so as to show the experimental approach.

Procedure for the reduction in the number of variables

A central task in determining whether an OMV mission results in a successful docking maneuver is to identify the relevant variables and to weigh the contribution that each makes in predicting a successful outcome. However, the use of a

regression model is inappropriate whenever the explanatory variables are inter-related. The unusual practice of interpreting regression coefficients as indicating a change in the response variable when the corresponding explanatory variable is increased by one unit and with all other explanatory variables held constant may not be valid if there is a strong association among the explanatory variables. Clearly the variables in the OMV simulation task are non-orthogonal: as time in the mission increases so too does the amount of fuel expended. Moreover, the experience of the human operator and delay in the presentation of the visual image following an action by the operator are also related to performance measures.

In situations where extreme multicollinearity is present the regression model may fail to provide any information for evaluating the importance of different variables on docking success. Since the explanatory variables are so highly correlated, each one may serve as a proxy for the others; thus, the explanatory power of the model would not be enhanced by the inclusion of additional variables. The condition of multicollinearity is not a modeling error but rather reflects deficit data. The data may be deficit because of insufficient observations or because the interrelationships among the variables are an inherent characteristic of the process being studied. The latter possibility seems to be the case with the OMV docking simulation procedure. The only recourse for analysis of this effect is to search for underlying causes that may explain the interrelationships among the variables. Through this

process, other variables may be identified that are the basic determinants of the relationship between a successful docking maneuver and the other variables.

Principle components analysis is one approach for identifying the linear combination of the regression coefficients. With this procedure variables are not divided into dependent and independent variables as in regression analysis. Instead the original variables are transformed into new, uncorrelated variables known as principle components. A principle component is a linear combination of the original variables; each component, unlike the original variables, is independent of all the others. If the components are represented geometrically, each would appear as a linear function and each function would be perpendicular to each other.

The principal components procedure is useful in reducing the number of variables without a loss of much information. The information measured in each principle component is expressed in its variance, i.e., the eigen value of the component. The first component is the most informative because it accounts for the largest share of the variance. Usually, the number of dimensions, i.e., principle components decided upon, is about one-third of the original number of variables. Since the components are uncorrelated, their use in a regression model overcomes the problem of multicollinearity.

Application of this analysis to the OMV simulation data would enable the identification of the several components that underlie task performance. The number of components selected would be based on a criterion of $100/\text{number of original variables}$

per cent of the total variance. A clue as to the 'meaning' or appropriate label assigned to the principle component is made by identifying those variables that correlate highly with that component. After the components are identified, a regression model using the components rather than the original variables would be employed to predict docking success of the OMV. Details of this analysis appear in Chatterjee and Price (1977) and in Price (1972).

OMV Workstation Data Base Augmentation

Experiment I

The purpose of Experiment I is to evaluate operator performance as a function of display configuration, time delays in the video picture and target attitude. The basic objective is to determine which type of display configuration results in best docking performance under various conditions which increase the difficulty of the docking task.

VARIABLES: Display Configuration X Time Delays X Target Attitude

PROBLEM: The effectiveness of an OMV mission is dependent on the ability of the operator to interact with the controls and displays and perform the tracking and docking functions. Operator input into the system once the OMV is in flight is through the hand controller by which he/she may guide the vehicle. Once the target has been visually acquired, the operator will perform the fine tracking functions to effect a successful docking with the target. Information is required on which type of display configuration results in most efficient and economical slewing and precision docking. Display configuration is important in being able to successfully dock with the target.

TEST OBJECTIVES

- I. Determine which display configuration results in the most efficient and economical slewing performance.

- II. Determine which display configuration results in most efficient and economical precision docking performance.
- III. Determine if slewing and precision docking can be performed with representative time delays in the video feedback.
- IV. Determine if slewing and precision docking can be performed with different target attitudes.
- V. Determine any interactions among the major variables.

OUTPUT/PRODUCT:

Operator performance on slewing and precision docking as a function of types of display configuration, target delay and target attitude will be obtained. Recommendations will be developed for display configuration requirements for slewing and precision docking. Design implications will be developed.

DATA MEASURES:

The dependent measures will describe the time it takes an operator to dock, docking assessment, fuel usage, and a subjective evaluation of the aesthetic value of each parameter.

HYPOTHESES

- I. Integrated Range and Range Rate displays result in performance superior to separate digital displays of the same data.
- II. An integrated OMV attitude display results in performance superior to separate digital display of the same data.
- III. The more complex the docking task, the more beneficial the integrated displays will be to the operator.

OPERATORS

Four experimental operators and four inexperienced operators will be used.

DEPENDENT MEASURES OR SYSTEM PERFORMANCE MEASURES:

Various measures will be taken including: number of successes (hits), time to slew to target docking envelope, time to dock, docking assessment (number of captured latches), fuel usage, fuel X time to dock, and the Cooper-Harper subjective evaluation of the parameters being tested.

EXPERIMENTAL DESIGN:

The design recommended is a split-plot design. The design has two between-block treatments, operator (O) and display configuration (D), and two within-block treatments, time delay (t) and target attitude (a). In this design, subjects will not receive all experimental conditions. Time delay and target attitude will be randomized for each subject. Assume 12 subjects (S_s) there would be a sample of 12 randomized sequences drawn from the $9!$ permutations possible. An example of one such sequence: $a_2 t_3, a_1 t_2, a_1 t_3, a_3 t_1, a_1 b_1, a_3 t_3, a_3 t_2, a_2 t_2, a_2 t_1$. Variables will be as follows:

Display Configuration: Integrated Range/Range Rate display vs. Digital Display vs. Integrated OMV attitude display

Time Delays: 0 seconds, 5 seconds, 10 seconds

Target Attitude: Stable, Spinning, Coning

Operator Experience: Inexperienced, Experienced

Operator Experience: Inexperienced, Experienced

DESIGN FORMAT:

Operator: Inexperienced vs. Experienced O₁ O₂

Display configuration: Range/Range Rate D₁
Digital D₂
Integral Attitude Display D₃

Time Delay: 0, 5, 10 seconds t₁, t₂, t₃

Target Attitude: stable, spinning, coning a₁, a₂, a₃

	a ₁	a ₁	a ₁	a ₂	a ₂	a ₂	a ₃	a ₃	a ₃
OD ₁₁	S ₁ =2								
OD ₁₂	S ₂ =2								
OD ₁₃	S ₃ =2								
OD ₂₁	S ₄ =2								
OD ₂₂	S ₅ =2								
OD ₂₃	S ₆ =2								

d_{1a1t1} d_{1a1t2} d_{1a1t3}
d_{1a2t1} d_{1a2t2} d_{1a2t3}
d_{1a3t1} d_{1a3t2} d_{1a3t3}

d_{2a1t1} d_{2a1t2} d_{2a1t3}
d_{2a2t1} d_{2a2t2} d_{2a2t3}
d_{2a3t1} d_{2a3t2} d_{2a3t3}

d_{3a1t1} d_{3a1t2} d_{3a1t3}
d_{3a2t1} d_{3a2t2} d_{3a2t3}
d_{3a3t1} d_{3a3t2} d_{3a3t3}

TABLE 4

SUMMARY TABLE SPLIT-PLOT

Operator: Inexperienced vs. Experienced o = p
 Display Configuration: D₁, D₂, D₃ d = r
 Time Delay: 0, 5, 10 seconds t = 9
 Target Attitude: Stable, Spinning, Conning a = w
 a₁, a₂, a₃

Source	df	df
Between Subjects	nod-1	71
SS Operator	O-1	1
SS Display	D-1	2
SS O x D	(o-1)(d-1)	2
SS Subject Within Groups	od(m-1)	66
Within Subjects	nop(ta-1)	576
SS Time Delay	t-1	2
SS T x O	(t-1)(o-1)	2
SS T x D	(t-1)(d-1)	4
SS T x O x D	(t-1)(o-1)(d-1)	4
SS Delay x Subject Within Groups	od(n-1)(t-1)	132
SS Attitude x Subject W/in Groups	a-1	2
SS O x A	(o-1)(a-1)	2
SS A x D	(d-1)(a-1)	4
SS A x O x D	(o-1)(a-1)(d-1)	4
SS A x subjects W/in Groups	(od(n-1)(a-1)	132
SS Time Delay x Attitude	(t-1)(a-1)	4
SS o x t x A	(o-1)(t-1)(a-1)	4
SS D x t x A	(d-1)(t-1)(a-1)	8
SS o x D x t x a	(o-1)(d-1)(t-1)(a-1)	8
SS A x t x Subject Within Groups	od(n-1)(t-1)(a-1)	264
SS Total	odtan-1	647

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OMV Control and Display Literature Review
A Preliminary Analysis*

I. Fog-M Console

- A. Fog-M Video Display
- B. Fog-M Control Grip
- C. Fog-M Trigger Switch
- D. Fog-M Joystick

II. Hand Controls

A. Types

- 1. Isotonic
- 2. Isometric

B. Linear Forces

- 1. Elastic
- 2. Viscous Friction
- 3. Inertia

C. Non-Linear

- 1. Friction

III. Displays

A. Types

- 1. Video
- 2. Audio
- 3. Digital
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B. Visual Aids

- 1. Reticle
- 2. Color Coding

C. Control Aids

- 1. Aiding
- 2. Quickening
- 3. Augmentation
- 4. Unburdening
- 5. Control/Display Ratio
- 6. Tactile Feedback
- 7. Force-Reflecting Feedback
- 8. Time Lag

*This analysis and review were conducted without access to the Phase B Contractors proposal which was proprietary at the time of this study.

ISOTONIC CONTROLS

A free-moving position control, which remains at the position at which it is placed. A true isotonic control is only an abstraction due to the fact that any control has some mass and friction, though proper design can reduce the resulting inertial and friction forces to negligible values (Van Colt and Kinkade, 1972).

- : No force is required for constant output (Van Colt and Kinkade, 1972).
- : Visual feedback of control position is available (Van Colt and Kinkade, 1972).
- : Isotonic controls are more subject to inadvertent inputs from operator and environment than isometric controls (Van Colt and Kinkade, 1972).
- : They do not return to zero when released (Van Colt and Kinkade, 1972).
- : They do not provide clearly defined zero output information (Van Colt and Kinkade, 1972).
- : Tracking error is generally higher, especially with high-frequency inputs, due primarily to phase lag at high frequencies (Van Colt and Kinkade, 1972).
- : A large output range can be controlled with very small manual forces (Van Colt and Kinkade, 1972).
- : Movement should be smooth in all directions (MIL-STD-1472C, 5.4.4.2.2.2).
- : The dimensions should be a minimum diameter of 6.5 mm and length of 150 mm (MIL-STD-1472C, 5.4.3.2.2.2).
- : The minimum resistance should be 3.3 N with a maximum of 8.9 N (MIL-STD-1472C, 5.4.3.2.3.3.2).
- : The maximum displacement should be 45 degrees (MIL-STD-1472C, 5.4.3.2.3.3.2).

ISOMETRIC CONTROL

A force transducing control (Van Colt and Kinkade, 1972).

- : Output returns to zero when force is removed (Van Colt and Kinkade, 1972).

- : Single-axis tracking, particularly of high-frequency inputs, is better with isometric controls than with isotonic ones, involving as much as a 2:1 reduction in error with rate controls (Van Colt and Kinkade, 1972).
- : There is less inadvertent input under vibration and G loading if good forearm support is provided (Van Colt and Kinkade, 1972).
- : A deadzone must be introduced in multi-axis tracking to prevent inadvertent cross-coupling between axes (Van Colt and Kinkade, 1972).
- : Continuous force application is required to maintain non-zero output with position control system or when tracking very low-frequency input signals, which may lead to operator fatigue during prolonged operation (Van Colt and Kinkade, 1972).
- : Controller output corresponds to force applied by operator (Van Colt and Kinkade, 1972).
- : Isometric joysticks are particularly appropriate for applications which require return to center after each entry or where operator feedback is primarily visual from some system response rather than kinesthetic from the stick itself or there is minimal delay and tight-coupling between control and input and system reaction (MIL-STD-1472C, 5.4.3.2.3.1, and NASA-STD-3000, 9.3.2.2).
- : The hand-grasped shaft should have limiting dimensions of 110-180 mm for shaft length, a maximum grip diameter of 50 mm, and clearances of 100 mm to the side and 50 mm to the rear (MIL-STD-1472C, 5.4.3.2.3.2).
- : Maximum force for full output should not exceed 118 N (26.7 lb.) (MIL-STD-1472C, 5.4.3.2.3.2).
- : No space is required for control movement (Van Colt and Kinkade, 1972).
- : An isometric stick is superior to an isotonic stick when the control system has oscillatory position control dynamics (Notterman and Page, 1962).

ELASTIC

Spring-loading resistance (Van Colt and Kinkade, 1972).

- : It applies force toward the null position when the control is displaced; hence it aids in identifying the null position and in making adjustments around it (Van Colt and Kinkade, 1972).

- : Resistance is proportional to control displacement, but is independent of velocity and acceleration (Van Colt and Kinkade, 1972).
- : It returns the control automatically to the same (null) position when the operator's hand is removed (Van Colt and Kinkade, 1972).
- : It permits quick changes in direction to be made (Van Colt and Kinkade, 1972).
- : It allows the operator's hand to rest on the control without activating it if there is sufficient resistance (preloading) at the null position (Van Colt and Kinkade, 1972).
- : It reduces the likelihood of undesired activation (Van Colt and Kinkade, 1972).
- : It provides the operator with feedback information concerning control position (Van Colt and Kinkade, 1972).
- : It provides the force gradient to be modified to provide special cues about the critical position of the control (resistance suddenly increases as a limit is approached) (Van Colt and Kinkade, 1972).
- : The relationship may be linear or non-linear (McCormick, 1964).
- : It varies with control displacement and thus provides a cue to the amount of displacement independent of the velocity and acceleration of the control (Van Colt and Kinkade, 1972).

VISCOUS FRICTION

Force operating opposite to output but proportional to the output speed (McCormick, 1964).

- : It is independent of displacement and acceleration (Van Colt and Kinkade, 1972).
- : It resists quick gross movements (Van Colt and Kinkade, 1972).
- : It reduces the likelihood of accidental activation (Van Colt and Kinkade, 1972).
- : It allows for smooth movement (Van Colt and Kinkade, 1972).
- : It permits rapid change in direction and small changes in position (Van Colt and Kinkade, 1972).

- : It provides feedback about the velocity of control movements, though it is questionable if this information can be used precisely (Van Colt and Kinkade, 1972).

INERTIAL RESISTANCE

Resistance to movement caused by the mass of the control (McCormick, 1964).

- : It varies directly with control acceleration but is independent of displacement and velocity (Van Colt and Kinkade, 1972).
- : It reduces the likelihood of accidental activation (Van Colt and Kinkade, 1972).
- : It resists sudden changes in velocity; hence it aids in making smooth movements or gradual changes in velocity (Van Colt and Kinkade, 1972).
- : It requires that large forces be applied to stop or start control movements quickly; hence it hinders any change in direction of movement (Van Colt and Kinkade, 1972).
- : It provides feedback about acceleration of control movements, though it is questionable if this information can be used precisely (Van Colt and Kinkade, 1972).
- : It increases the difficulty of making small or precise adjustments quickly because of the danger of overshooting (Van Colt and Kinkade, 1972).
- : It can be used to maintain control movements without requiring the continual application of force (Van Colt and Kinkade, 1972).

FRICTION

Resistance to movement (Van Colt and Kinkade, 1972).

- : Static friction decreases sharply when the control starts to move; hence sliding friction is independent of displacement velocity and acceleration (Van Colt and Kinkade, 1972).
- : Coulomb friction continues as a resistance to movement, but is not related to speed or displacement (McCormick, 1964).
- : By increasing or decreasing friction as a function of control position, gross control position can be identified by feel (Van Colt and Kinkade, 1972).

- : Static friction tends to hold the control in position and thus reduces the likelihood of undesired activation (Van Colt and Kinkade, 1972).
- : Sufficient static friction allows the operator's hand to rest on the control without activation (Van Colt and Kinkade, 1972).
- : It increases the difficulty of making precise settings and small changes in the position of the control (Van Colt and Kinkade, 1972).
- : It is difficult to design a control with a constant amount of friction. However, a "locking" device can be provided which allows friction to be varied (Van Colt and Kinkade, 1972).
- : Overcoming friction in heavy controls can be tiring (Van Colt and Kinkade, 1972).

VIDEO DISPLAY

A presentation of data by the use of video equipment.

- : Target signal should subtend not less than 6 mrad (20 minutes) of visual angle and not less than 10 lines of resolution elements (MIL-STD-1472C, 5.2.4.1).
- : Ambient illuminance should not contribute more than 25% of screen brightness through diffuse reflection and phosphor excitation (MIL-STD-1472C, 5.2.4.3).
- : The luminance range of surfaces immediately adjacent to scopes should be between 10 and 100% of screen background luminance (Bailey, 1982).
- : Luminance (radiant intensity of a surface measured in millilamberts should be 25 ml to 50 ml (Bailey, 1982).
- : A contrast (ratio of background luminance minus symbol luminance to background luminance plus symbol luminance) ratio of 30 (contrast of 94%) is preferred and 15 (contrast of 88%) is acceptable (Bailey, 1982).
- : A regeneration rate of 60 Hz, the same as home television receivers, is sufficient to prevent perception of disturbing flicker (Bailey, 1982).
- : At least 50 scan lines per inch should be used to provide illusions of continuous characters (Bailey, 1982).
- : Minimum dot matrix is a character height of 7 dots (5x7 dot matrix), while 9 dots (7x9 dot matrix) is preferred (Bailey, 1982).

- : Reflected glare should be minimized by proper placement of the scope to the light source, use of a hood or shield, or optical coatings or filter control over the light source (MIL-STD-1472C, 5.2.4.7).
- : Characters should be at least .17 inches in height (Bailey, 1982).
- : Distance between lines should be at least 50% of character height while 66% is preferred (Bailey, 1982).
- : Spacing between adjacent characters should be at least 10% of character height (Bailey, 1982).
- : Character width should be between 70 and 85% of character height (Bailey, 1982).

AUDIO DISPLAY

A data presentation by the use of auditory stimuli.

- : Suitable for short messages (Morgan, et al., 1963; and Bailey, 1982).
- : Suitable when response time is important (Morgan, et al., 1963; and Bailey, 1982).
- : Suitable when the message need not be referred to later (Morgan, et al., 1963; and Bailey, 1982).
- : Suitable when receiving location is not suitable for visual reception (Bailey, 1982).
- : Suitable when the message deals with events in time (Morgan, et al., 1963).
- : Suitable when the message is simple (Morgan, et al., 1963).
- : Should cease only after user response (Bailey, 1982).
- : Should be of a distinguishable frequency (Bailey, 1982).
- : Suitable when the user's task requires considerable movement (Morgan, et al., 1963).
- : Complex messages should consist of an attention-demanding signal and a designation signal (McCormick, 1964).
- : The same signal should designate the same information at all times (McCormick, 1964).

- : Suitable when it is desirable to warn, alert, or cue the operator to subsequent additional response (MIL-STD-1472C, 5.3.1.1.d).
- : Caution signals should be readily distinguishable from warning signals (MIL-STD-1472C, 5.3.2.3).
- : The frequency range for warning signals should be between 200 and 5000 Hz, and if possible, between 500 and 3000 Hz (MIL-STD-1472C, 5.3.3.1.1; and NASA-STD-3000, 9.4.4.3.4.1).
- : Should not be of such intensity as to cause discomfort or "ringing" in the ears as an after-effect (MIL-STD-1472C, 5.3.3.2.1; and NASA-STD-3000, 9.4.4.3.4.1.b.3).
- : When reaction time is critical, and a two element signal is necessary, an alerting signal of 0.5 second duration shall be provided. All essential information should be transmitted in the first 2.0 seconds of the identifying or action signals (MIL-STD-1472C, 5.3.2.2.1).
- : The first 0.5 second of an audio signal requiring fast reaction shall be discriminable from the first 0.5 second of any other signal that may occur (MIL-STD-1472C, 5.3.4.3.3; and NASA-STD-3000, 9.4.4.3.4.1.e.3).
- : When the operator is wearing earphones covering both ears during normal operation, the audio alarm signal shall be directed to the operator's headset as well as to the work area (MIL-STD-1472C, 5.3.4.2.4; and NASA-STD-3000, 9.4.4.3.4.1.d.3).

DIGITAL DISPLAY

A display of discrete signals, usually appearing in binary form, consisting of a series of pulses that when combined in groups represent a sequence of discrete values or numbers (Bailey, 1982).

- : Suitable for reading precise, static, or slowly changing values (Bailey, 1982).
- : Suitable for making exact numerical settings (Bailey, 1982).
- : Suitable when determining the rate of change is difficult (Bailey, 1982).
- : Requires little space (Bailey, 1982).
- : Reading a digital display's rapidly changing values is difficult (Bailey, 1982).
- : Interpolating is difficult when two numbers are partially visible in a window (Bailey, 1982).

ANALOG DISPLAY

A display of signals that take on continuous values, changing analogously to some system variable (Bailey, 1982).

- : Suitable when interpolation between numbers is required (Bailey, 1982).
- : Suitable when rate or trend information is required (Bailey, 1982).
- : Suitable for making check readings (Bailey, 1982).
- : Frequently requires more panel space than other display types (Bailey, 1982).
- : Scale length is fixed and therefore limited (Bailey, 1982).

RETICLES

Devised markings or fibers placed at an approximate location in an optical instrument to provide a convenient reference or scale. (Biberman, 1966).

- : Reticle lines should be thin enough so as not to obscure targets, but thick enough to be easily seen and should subtend a minimum of 600 urad (2 min) at the eye (MIL-STD-1472C, 5.11.3.1).
- : Reticle patterns should be as simple as possible and restricted to one main mission per reticle glass (MIL-STD-1472C, 5.11.3.11.2).
- : Line reticles should be used in preference to reticles containing one, two, or three central spots (MIL-STD-1472C, 5.11.3.11.3).
- : A small cross or very small circle should be used in preference to a dot (MIL-STD-1472C, 5.11.3.11.3).

COLOR CODING

The use of a certain color to convey a specific meaning.

- : Red should be used to indicate that the system or a part of it is inoperative, or that a successful mission is not possible until appropriate corrective or override action is taken (MIL-STD-1472C, 5.2.2.1.18.a).
- : Flashing red shall be used only to denote emergency conditions which require operator action to be taken without undue delay (MIL-STD-1472C, 5.2.2.1.18.b).

- : Yellow should be used to advise an operator that a condition exists which is marginal (MIL-STD-1472C, 5.2.2.1.18.c).
- : Green should be used to indicate that the monitored equipment is in tolerance or a condition is satisfactory and it is all right to proceed (MIL-STD-1472C, 5.2.2.1.18.d).
- : White should be used to indicate system conditions that do not have "right" or "wrong" implications, such as alternative functions or transitory conditions provided such indication does not imply success or failure of operations (MIL-STD-1472C, 5.2.2.1.18.e).
- : Blue may be used as an advisory light, but should be avoided (MIL-STD-1472C, 5.2.2.1.18.f).
- : On indicators where zone markings are used to indicate various operating conditions, the primary colors shall be limited to red, yellow, orange, and green (NASA-STD-3000, 9.5.3.2.i.7).

AIDING

Parallel feed-forward compensation of the machine portion of the control system which alters the frequency response and transient response of the system in a completely predictable manner (McCormick, 1964).

- : It relieves the operator of such functions as integration, differentiation, and addition and provides for these to be performed by the system (McCormick, 1964).
- : Is generally of greatest use where the input is relatively constant, where there is minimal lag and backlash, and where the aided-tracking time constant (the ratio between the change in position of the "follower" of the display and its range of change) is relatively optimum (around 0.5 seconds) (McCormick, 1964).
- : The number of terms used in aiding should exceed by one the derivative of the input that is constant (Morgan, et al., 1963).
- : The aiding constant should be confirmed experimentally for each specific situation (Morgan, et al., 1963).
- : More control movements are required to obtain a simple machine output with aiding than in unaided tracking (Morgan, et al., 1963).

QUICKENING

A modification of the information displayed to the operator that shows him more directly what control response he should make to bring about the desired system output (McCormick, 1964).

- : It is most useful with systems that have complex physical dynamic characteristics (McCormick, 1964).
- : It simplifies the operator's tracking task and results in improved performance, except in those cases where either the original task is very simple or the operator has already reached a high level of skill in performing it (Birmingham, et al., 1954).
- : It minimizes the time required to train an operator (Holland and Henson, 1956).
- : It frees some of the operator's time so that he can perform other duties concurrently (Birmingham, et al., 1954).
- : It is usually applied to higher-order, slow-responding systems in the form of derivative signals summed with the system output signal back to the display (Van Colt and Kinkade, 1972).
- : It is useful when necessary to stabilize an unstable or marginally stable system (Van Colt and Kinkade, 1972).
- : It eliminates most of the detrimental effects resulting from "reversal errors" (i.e., from the operator's starting to move his control in the wrong direction when correcting an error) and thereby, reduces the importance of such human engineering considerations as direction of movement and frame-of-reference relationships (Birmingham and Taylor, 1954).
- : It permits the operator with less ability to perform the tracking task (Morgan, et al., 1963).
- : It permits the execution of a desired maneuver in a very short time, the limiting factor being the performance capabilities of the vehicle rather than the skill of the operator (Morgan, et al., 1963).
- : It permits repeatability so that a desired maneuver will occur in the same way each time it is performed (Morgan, et al., 1963).
- : It makes system performance much less dependent on human performance: the designer, rather than the operator, determines what the performance characteristics of the system will be (Morgan, et al., 1963).
- : It permits safety terms to be incorporated into the display (Morgan, et al., 1963).

- : It does not provide the operator with information about the actual state of the system (Morgan, et al., 1963).
- : To be useful when there are high frequencies present in the input, additional circuitry must be provided (Birmingham and Taylor, 1954).
- : Although, theoretically, it reduces to one the number of displays required by the operator, in actual practice, it usually adds an extra display because the "normal" displays showing the actual state of the system, will, in most cases, still be desired by the operator (Morgan, et al., 1963).
- : If the operator achieves a perfect tracking performance when using the quickened display, he will always achieve his desired output in the same manner (e.g., by following the same flight path,) but the best manner for any one situation is not necessarily the best for others (Morgan, et al., 1963).
- : It is possible to use a quickened display and still vary the manner in which the final output is achieved (Morgan, et al., 1963).
- : Although the display responds more quickly to the operator's inputs, the sluggishness of the actual system is unaffected (Van Colt and Kinkade, 1972).
- : It can result in poor response to time-varying command signals unless the command signal is passed through an anti-bias network (Van Colt and Kinkade, 1972).

DISPLAY AUGMENTATION

The performance of one or more of the outer-loop controller functions by the mechanical elements, operating on signals before they reach the operator and displaying the computed result to him (Kelly, 1968).

- : Operations are performed on the operator's input (Kelly, 1968).
- : Attention is transferred from outer-loop goal to inner-loop functioning (Kelly, 1968).
- : It can employ man's muscular strength at the control junction in the inner loop (Kelly, 1968).
- : The operator is kept aware of the control signal (Kelly, 1968).
- : It requires higher frequency and more complex human output (Kelly, 1968).

UNBURDENING

Raising the order of a control system by removing the "burden" of performing as an integrator to meet the requirements of system performance (Van Colt and Kinkade, 1972).

- : When increasing the order of the system, care must be taken not to require additional compensation by the operator (Van Colt and Kinkade, 1972).
- : Unburdening is also used in reference to changes in the control system which remove the requirement for the operator to act as differentiator, which is more properly referred to as aiding if done by adding feed-forward loops (Van Colt and Kinkade, 1972).

CONTROL-DISPLAY RATIO

The ratio of the distance of movement of the control to that of the moving element of the display. For linear and near-linear controls that affect linear displays, the C/D ratio is defined as the ratio of the linear distance of control displacement to the distance of the resulting display movement, with control displacement being measured from the point where the operator's hand grasps the control. For small rotary controls that affect linear displays, it is defined as the ratio of the number of control rotations to the distance of display movement (Morgan, et al., 1963).

- : An increase in the C/D ratio will increase slewing time because of the longer movements required. For linear controls, slewing time is only slightly greater for long movements than for short ones (Barnes, 1936; Brown and Slater-Hammel, 1949; Brown, et al., 1948; and Peters and Wenborne, 1936).
- : Fine-adjusting (placing the control in precisely the final, desired position,) time is reduced either by increasing the C/D ratio or by easing the tolerance requirements (Jenkins and Connor, 1949).
- : Display size, tolerance, viewing distance, and time delay each affect the optimum C/D ratio (Morgan, et al., 1963).
- : A low C/D ratio is one where a slight control movement brings about a marked change in the display (Morgan, et al., 1963).
- : Control/display ratios for continuous adjustment controls shall minimize the total time required to make the desired control movement (i.e., slewing time plus fine adjusting time), consistent with display size, tolerance requirements, viewing distance, and time delays (MIL-STD-1472C, 5.1.4.1; and NASA-STD-3000, 9.2.3.2.9.A.a).

- : When a wide range of display element movement is required, small movement of the control should yield a large movement of the display element (MIL-STD-1472C, 5.1.4.2; and NASA-STD-3000, 9.2.3.2.9.A.b.1).
- : When a small range of display movement is required, a large movement of the control shall result in small movement of the display, consistent with accuracy requirements (MIL-STD-1472C, 5.1.4.2; and NASA-STD-3000, 9.2.3.2.9.A.b.2).
- : With counters, the C/D ratio should be such that one revolution of the knob produces approximately 50 counts (MIL-STD-1472C, 5.1.4.8; and NASA-STD-3000, 9.2.3.2.9.A.e).
- : Correct control-display movement relationships will enhance system performance by decreasing reaction time, reducing the frequency of incorrect initial control movements, improving the speed and precision of control adjustment, and decreasing learning time (Van Coat and Kinkade, 1972).
- : The importance of control-display relationships increases directly with the number of control actions, the nonsequential nature of control actions, the discontinuity, or number of interruptions, in the control sequence, and the operator's stress level (Van Coat and Kinkade, 1972).

TACTILE FEEDBACK

The use of the skin as a means of communication (McCormick, 1964).

- : Tactile stimulation can be accomplished by presenting mechanical, thermal, chemical, or electrical energy to the skin (Kantowitz and Sorkin, 1983).
- : Tactile sense is categorized as passive touch, which involves skin stimulation, and active touch, where the user explores an object or surface with the fingers or hand (Kantowitz and Sorkin, 1983).
- : Wearing protective equipment can seriously degrade the tactile feedback (Kantowitz and Sorkin, 1983).
- : A visual plus tactile system has been shown to improve tracking performance over a visual system in that providing error rate information via the auxilliary tactile channel apparently is an effective way to add "quickenning" information (Hirsch, 1974).

FORCE-REFLECTING FEEDBACK

Feedback derived from the force required to overcome the resistance of a control device (McCormick, 1964).

- : It is sensed largely through the tactile sense (McCormick, 1964).
- : The amplitude of movement is sensed through the kinesthetic sense from the proprioceptors in the joints and muscles (McCormick, 1964).
- : In attempting to reproduce pressures under 5 pounds, the errors are proportionately greater than for heavier pressures (Jenkins, 1947).
- : If varying levels of pressure discrimination are to be made, the equipment should provide a wide range of pressures up to 30 to 40 pounds (Jenkins, 1947).
- : Where distance of movement is limited, pressure cues are useful as guides to the appropriate control of control devices (McCormick, 1964).

TIME DELAY

The time between a control input and a system response (McCormick, 1964).

- : Time delay is virtually inherent in any man-machine system (McCormick, 1964).
- : It consists of lag in the system itself and in human reaction time (McCormick, 1964).
- : Transmission lag refers to a situation in which there is a constant delay between input and output; the output is identical to the input, but simply follows it, temporally, after a constant time interval (McCormick, 1964).
- : Exponential lag refers to the situation where the output follows essentially an exponential function following a "step" input (McCormick, 1964).
- : One study has found no difference in tracking errors between zero time delay and a 1 second delay, but there were significant increases with longer lags (Wallach, 1961).
- : A substantially linear relationship between amount of delay and the degree of degradation of compensatory tracking performance has been found for lags beyond 0.15 seconds (Levine, 1953).

- : With high control/display ratios, longer time lags are not serious, and may improve performance (Rockway, 1957).
- : The optimum delay between control and display depends partially on the magnitude of display change produced by a given control input (Rockway, 1957).

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