ILLUMINATION REQUIREMENTS FOR OPERATING A SPACE REMOTE MANIPULATOR

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INTRODUCTION

Critical issues and requirements involved in illuminating remote manipulator operations in space help establish engineering designs for these manipulators. A remote manipulator is defined as any mechanical device that is controlled indirectly or from a distance by a human operator for the purpose of performing potentially dangerous or hazardous tasks to increase safety, reliability, and efficiency. Future space flights will rely on remote manipulators for a variety of tasks including satellite repair and servicing, structural assembly, data collection and analysis, and performance of contingency tasks. Carefully designed illumination of these manipulators will assure that these tasks will be completed efficiently and successfully.

Studies concerning the influence of illumination on operation of a remote manipulator are few. Available results show that illumination can influence how successfully a human operates a remote manipulator. Previous studies have indicated that illumination should be in the range of 400-600 footcandles, the currently recommended range for fine to medium assembly work tasks [1, 2, 3, and 4]. However, on-orbit operations have demonstrated that effective operation can be performed under illumination levels between 100-500 footcandles provided that specularity and glare are minimized. Increasingly complex and finer work tasks would necessarily require an increase in illumination [1, 2, and 3]. Brightness should not exceed 300-450 footlamberts (roughly equivalent to a zenith sky or slightly brighter [3]) so as to eliminate glare and possible blinding of the operator. The reflectance percentage of the manipulator and target should be about 75%, if possible [5]. The beneficial aspect of high specularity is that detection distances may be as great as 5 miles during rendezvous operations [5]. Reflectance is an especially critical illumination-related parameter because a target object and a manipulator should be visible to a human operator from distances of at least 30-40 meters.

Remote manipulators and their task and target objects are operated optimally when direct and indirect glare is eliminated and lighting tends to be diffuse. Several ways exist to reduce glare: position light sources outside the operator's line of sight, use low-intensity light sources, increase luminance of the area around glare sources (direct glare), position light sources so a minimum amount of light is directed toward the eyes to prevent frontal and side blinding, and use luminaires with diffusing or polarizing lenses. Reflective surfaces should diffuse the light (flat paint, nongloss paper, and textured finishes). Illuminance levels should be kept as low as possible and use indirect lighting [2, 4]. A neutral density filter with a transmission of 20 percent can help reduce general reflected glare, except for the very harsh specular type, to an acceptable level [6].

Design of lamp lenses is an important factor to be considered in establishing lighting requirements. Lenses distort light distribution and can otherwise alter viewing conditions and may contribute to poor operator performance. Previous studies indicate that a planar-planar lens is probably the best because proper illumination levels will be maintained and contrast ratios are adequate [7]. Planar-planar lenses are currently used in Space Shuttle cargo bay lights.

MAJOR ISSUES

Literature surveys, evaluation of published experimental results, and consideration of requirements in Earth-based operations suggest that seven major issues may be identified as major contributors to establishing illumination requirements for a remote manipulator in space. These seven issues are listed and discussed below.

(1) *Sun angles and their influence on reflectance/viewing characteristics of remote manipulators.* Wheelwright [5, 6] has shown experimentally, with the use of scale models, the effects that sun angles have on the operation of the remote manipulator system on the Space Shuttle. Effects of sun angles depend largely on the viewing configuration. Remote manipulator teleoperations should avoid direct sun viewing to prevent blinding of the operator. Specular glare, veiling lumens, and extremely bright areas occur at various sun angles. Although objectionable, most on-orbit operations can still be completed. Reorientation of the viewing angle by no more than 5 degrees will, however, produce more favorable lighting conditions [6].

(2) *Reflectance properties of the manipulators under solar illumination and artificial lighting.* Comparison of the reflectance properties of manipulators under solar and artificial lighting is important to establish when and how each lighting regime can be used to advantage for optimum performance, to determine proper artificial light sources, and to determine what special filters might be necessary to enhance recognition and minimize specularity. Because solar light is collimated, special considerations may involve reflectance characteristics so as to minimize deleterious edge effects encountered in on-orbit operations.

(3) *Recognition and reflectance properties of task structures and target objects.* Recognition of task structures and target objects is important in order to optimize operations and to reduce hazards associated with incorrect identification. Target-background contrast ratios of at least 0.6 should be used to attain optimum size discrimination in two-target tasks. Size discrimination performance depends on target-background contrast. With contrast ratios of at least 0.6, the linear dimension size discrimination is on the order of 0.10. A reduced contrast ratio of 0.125, however, raises the threshold value to 0.30. Brightness discrimination between two targets is enhanced for contrast values of 0.25 or greater [8]. Some tasks may involve recognition of alpha-numeric characters. Character density, character contrast, viewing distance, and monitor size are some of the variables that can affect correct identification of alphanumeric characters [8].

(4) *Search and rendezvous requirements using running lights of a free-flying remote manipulator.* Establishing search and rendezvous requirements is critical because docking with a remote, free-flying manipulator will be an essential activity in on-orbit operations. Remote manipulator docking and operation require that the operator be able to acquire depth and range information from the visual system. Range estimation depends on target size, brightness, and contrast [8] Configuration of running lights is important because recognition of form and orientation of axes will be critical for successful rendezvous and docking operations.

(5) *Tracking and recognition of remote manipulators by direct vision and monitor viewing.* The issue of direct vision and TV monitor viewing remains unresolved. Evidently, each viewing method has advantages under certain conditions. Viewing is the primary form of feedback to the operator regarding manipulator position, orientation, and rate of movement. The illumination system and viewing system are interdependent and together result in operator perception of manipulator motion.

(6) *The influence of light intensity, position, and type on operator performance.* A few studies have measured how operator performance is influenced by light intensity, position, and type. Operator physical and

mental workload may be dramatically affected by these parameters. Onboard lighting is effective for close-in illumination of shapes and spaces hidden in deep shadow. A variety of lights differing in illumination output, power consumption, spectral specularity, beam width, and efficiency will probably be necessary for on-orbit operations. Results suggest that performance is best maximized by tailoring light intensity, position, and type to the specific task [9].

(7) *The effects of shadow patterns on operator interpretation and performance.* The interpretation of shadow patterns could have a significant effect on operator performance but just exactly what these effects are remains to be determined. Local task-specific lighting may be necessary to overcome some of the problems associated with shadow patterns. Total elimination of shadows appears impossible, however, and more research is needed to determine cognitive processes involved in shadow interpretation.

All seven issues must be resolved in the context of realistically achievable physical conditions in space. Perhaps two of the most limiting conditions will be the power availability (the power requirements for the use of remote manipulators) and thermal conditions. Power is a necessary, but limited commodity in a space environment and will be a restrictive factor in remote manipulator operations. Illumination designs and hardware must account for potential problems in heat dissipation.

DISCUSSION

Identification, characterization, and analysis of each of the seven major issues will contribute to engineering design plans for a successful human operator-remote manipulator interface. An initial approach to determine the relative importance of each issue with respect to remote manipulator operation is to establish some critical visual activities and how they are related to each of the seven issues. A suggested relationship among the seven issues discussed in this paper and six critical visual activities as defined by Huggins, et al. [10] is displayed in Table 1. Critical visual activities were defined and studied by Huggins, et al. [10] in their evaluation of human visual performance for teleoperator tasks.

In this study, we define acuity as keeness of perception, discrimination as the ability to distinguish among objects, and recognition as the ability to identify an object. Using these definitions, we suggest which of the six critical visual activities are most likely to be affected by each of the seven issues. In no way is this intended to mean that some activities are not affected by all the issues; indeed, each issue will have some, albeit small in some instances, influence on each activity. Instead, we infer some critical visual activities to be more vulnerable to anticipated specifications defined by the issues than others. Expectations will most probably change as new data become available, so the suggested relationships given in Table 1 should not be considered as fixed. Rather, the given relationships are intended only as a guideline to help plan, evaluate, and interpret future studies and, possibly, designs.

Once each illumination parameter has been specified, continuing human factors engineering studies should evaluate the various kinds of mental models used by an operator. Mental models can be used to account for human interactions with a remote manipulator by helping to define the cognitive processes involved in human-remote manipulator interactions [11]. Definition of mental models used by an operator of a remote manipulator could help establish lighting arrangement and intensity, brightness and illumination requirements, and mental processes associated with shadow interpretation.

The major issues identified in this study may also be helpful in defining illumination requirements in other applications using indirect human operation and in creating optimum engineering designs for remote manipulators used in undersea tasks, assembly-line work, and in the nuclear industry.

TABLE 1

Summary of suggested relationships among the illumination issues discussed in this paper and critical visual activities evaluated by Huggins, et al. [10]. (See text for definition of terms and issues.) Each X shows what critical activities are most likely to be affected by the issues discussed in the text.

	CRITICAL VISUAL ACTIVITY					
ILLUMINATION ISSUE	Acuity Size	Size Estimation	Form Discrimination	Brightness Discrimination	Pattern Recognition	Depth Distance
Reflectance of remote manipulator	X		X	X		X
Solar vs. artificial lighting			X	X	X	
Reflectance of target	X	X		X		X
Effect of running lights			X			X
Direct vision vs. TV	X				X	X
Lighting parameters	X	X	X			X
Effect of shadows	X	X	X		X	X

SUMMARY

(1) Preliminary guidelines for illumination requirements in remote manipulator tasks in space are suggested: illumination should be in the range of 400-600 footcandles (although under some circumstances a range of 100-500 footcandles could suffice), brightness should not exceed 300-450 lamberts, reflectance of target/task objects should be about 75% (we suggest a range of between 50-75%), and an optimum contrast ratio between target and background is at least 0.6%.

(2) Seven major issues related to illumination of a remote manipulator in space are discussed: the influence of sun angles on reflectance/viewing characteristics of remote manipulators, reflectance properties of the remote manipulator under solar and artificial lighting, task/target object recognition and reflectance properties, rendezvous requirements, tracking and recognition of remote manipulators by direct vision and TV monitors, lighting parameters (such as intensity, position, and type), and the effect of shadow patterns on operator interpretation and performance.

(3) Critical visual activities, such as acuity, discrimination processes, and recognition tasks in the optimum operation of a remote manipulator, are known to be influenced by the illumination environment. Future research intended to measure and interpret fully the influence of illumination should use scale-model and full mockup testing to evaluate human operator performance under various illumination regimes.

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