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Perceptual Challenges of Lunar Operations

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ABSTRACT

Current plans to conduct operations near the lunar poles will result in low sun angles, exacerbating visual problems associated with shadowing and glare. We discuss the perceptual challenges these conditions will present to the human explorers, and consider some possible mitigations and countermeasures.

INTRODUCTION

NASA's Constellation Program currently proposes to resume crewed exploration of the Moon in the 2020 timeframe, with missions to the polar regions more often than the equatorial zones visited by Apollo. The lunar environment provides different perceptual cues than those available on Earth. There are no ambient sounds or scents. The suits humans must wear to survive greatly attenuate and alter tactile stimulation. Even the gravitational-inertial cues differ, due to the Moon's lower gravity. Consequently, there is a heightened dependence on visual cues; yet many of these are altered or compromised as well.

The absence of an atmosphere impacts illumination conditions and distance cuing. Further, NASA's plans to conduct operations near the lunar poles will result in low sun angles, exacerbating problems associated with shadowing and glare. We will discuss three challenges these conditions will present to the human explorers, and consider some possible countermeasures to mitigate the high contrast and glare.

AMBIENT ILLUMINATION

The 1964 edition of NASA’s Bioastronautics Data Book (1) contains data that show how luminous objects will be on the moon as compared to on earth. As Table 1 shows, the Earth’s atmosphere is quite transparent (attenuating visible wavelengths by less than a factor of two). The human eye is thus well adapted to the level of visible sunlight on the moon (but needs protection from the UV because of the absence of atmospheric ozone). The human eye can, of course, see well in moonlight; thus, it will be fine in earthlight (which is 70 to 150 times more illuminating than moonlight because of the Earth's larger angular area (14X) and its higher reflectivity (5-11X, depending on cloud cover). Although the Moon appears white in the dark sky, its reflectance of 0.07 indicates that it will, on average, look dark gray in the presence of white objects. The human eye even works in starlight, but with limited resolution because of the small rate of photon absorptions.

Luminance	Source
2.2 billion	Sun from Moon
1.4 billion	Sun from Earth
30,000	Sunlit clouds from Moon (r=0.8)
14,000	Earth from Moon in January, no clouds (r = 0.39)
6,400	Sky on a clear day
3,800	Moon from space (r = 0.073)
2,500	Moon from earth
1,600	Sky on a cloudy day
300	White TV screen or computer monitor
64	White paper good reading light
2.5	Snow full moonlight
0.064	Lower limit useful color vision
0.024	Earth from space in full moonlight
0.0032	Upper limit night vision
0.000032	Absolute threshold dark-adapted human eye

Table 1. Luminance in candelas per square meter. The reflectance (r) is considered to be invariant with wavelength. Adapted from the 1964 Bioastronautics Data Book (NASA SP-3006, Paul Webb, M.D., ed.).

The challenging aspect of lunar illumination, then, is in the shadows. On Earth the sky illuminates the shadows. On the Moon, in the worst case, this is left to the stars.

POLAR EFFECTS

The Apollo missions visited equatorial regions. Most Constellation missions will be conducted in the polar regions, affording significant scientific benefits and some logistical advantages. For example, mission durations will be able to extend beyond the lunar day; temperature gradients will be less extreme. However, the low sun angle will create even more challenging ambient illumination conditions. It will create long shadows that have no sky to illuminate them; further, the sun will be as bright near the horizon as when overhead. Unattenuated by an atmosphere, the sun will impose a fierce glare source for viewing objects in its direction.

VISUAL DYNAMIC RANGE

Film cameras can typically accommodate a wide range of average luminance by adjusting the iris area, the shutter speed, and/or the film grain. However, for a given image frame, these factors are fixed: the dynamic range of a particular image is that of the film. Digital cameras are similar, with the dynamic range of a particular frame determined by individual pixels.

The human visual system can accommodate a very wide range of average luminance. The pupil size is an image-wide adjustment, but it only adjusts by a factor of ten. The other adaptation factors function locally and allow different sensitivity to different parts of the image. Both the photopigment bleaching and the neural adaptations, which together account for most of the adjustment to the average luminance level, are local in nature (2). As shown in Figure 1, the stadium shadow in a baseball game affects the TV audience more than the live audience due to this superior "local gain control" of the human visual system.

Figure 1. Bright sunlight on half of old Busch Stadium is minor annoyance for live viewing, but presents a major challenge for television cameras.

Unfortunately, there are other factors that prevent us from being able to see in a starlit shadow in the presence of sunlit objects. One is that our adaptation process is slow. The adaptation to increased light levels has a time constant in the range of seconds; dark adaptation has a time constant in the range of minutes (3). Another limitation is that our region of high-resolution vision (the fovea) is constrained to a diameter of one or two degrees. If the fovea is pointed at a bright object for even a brief time, the slow nature of dark adaptation becomes critical – it takes minutes to recover high-resolution vision for darker objects and regions.

A final problem is that there is significant light scatter within the eye (mainly occurring in the crystalline lens). Light scattering parameters for astronauts are not available for system designers. Light scattering by the lens is tested in the clinic by shining a slit on the lens and looking at the light scattered back; however, this back-light scatter is not necessarily predictive of the light scattered forward.

In order for astronauts to view the lunar environment directly, it is necessary to both provide protection from harmful rays, and to aid their adaptation to the extreme, dynamic illumination conditions.

PROVEN COUNTERMEASURES - SUIT VISORS

To date, the primary mitigation for these visual challenges has been visors integrated into the helmet of the astronaut's EVA suit. This technology is designed to provide thermal/UV protection and light attenuation via passive filtering.

APOLLO'S LUNAR EXTRAVEHICULAR VISOR ASSEMBLY (LEVA) - Latched over the “Bubble Helmet”, the LEVA consisted of a thermal cover, two visors, and three eye-shades. The visors were layered over each other (see Figure 2). The inner "protective visor" was made of ultraviolet-stabilized polycarbonate plastic and filtered UV and rejected IR. The outer "sun visor" was made of high-temperature polysulfone plastic and filtered visible light and most ultraviolet and infrared rays.

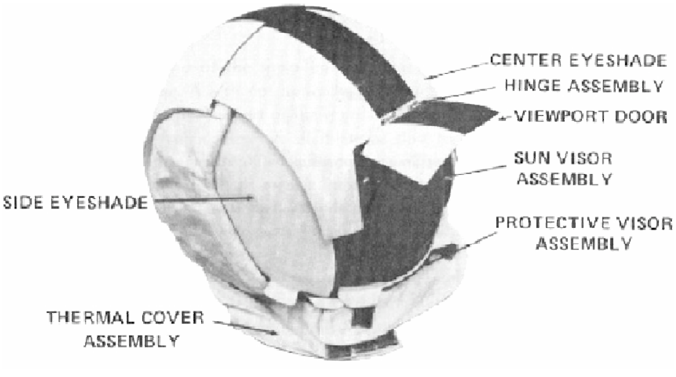

Figure 2. The Lunar Extravehicular Visor Assembly (LEVA) used during the Apollo EVAs.

SHUTTLE EVA SUIT VISOR – As shown in Figure 3, the shuttle EVA helmet visor is similar to that used for Apollo. Its solar shield protects with a vapor-deposited gold thin-film. The EVA self-portrait in Figure 3 also shows reflections of the Earth, the Shuttle's Remote Manipulator System, and the Nikon F5 used to capture the moment.

The suit and visor systems developed for Shuttle missions are also used on ISS EVAs, and can be considered state-of-the-art technology.

Figure 3. Current EVA visor technology.

A serious drawback to these passive visor systems is that they provide the same degree of light attenuation across the visual field. They therefore fail to adequately address the visual "hot spots" created by glare, and may further mask shadowed regions. This technology may thus prove inadequate to cope with the extreme visual challenges of polar EVAs. Hence, we need to consider new ways to view these ancient moonscapes.

POTENTIAL COUNTERMEASURES – BUILDING BETTER SUN SHIELDS

Advances in electro-optics make it possible to consider more creative mediations to aid vision during EVAs. The first set of alternatives we will consider involves using these advanced technologies to develop systems that better facilitate direct viewing of the scene. These systems will focus on mitigating ambient glare and providing illumination to shadowed regions of the visual field.

DYNAMIC VISOR SYSTEM - Researchers at NASA's Johnson Space center developed the idea of using an LCD panel as a visor so that the attenuation is spatially programmable (4). A small camera mounted on the helmet could be used to locate the sun or Earth, then the corresponding pixels could be darkened to block out the glare and adaptation source (see Figure 4). The system could also generate localized filters to darken bright objects when the goal was to see as well as possible into dark shadows.

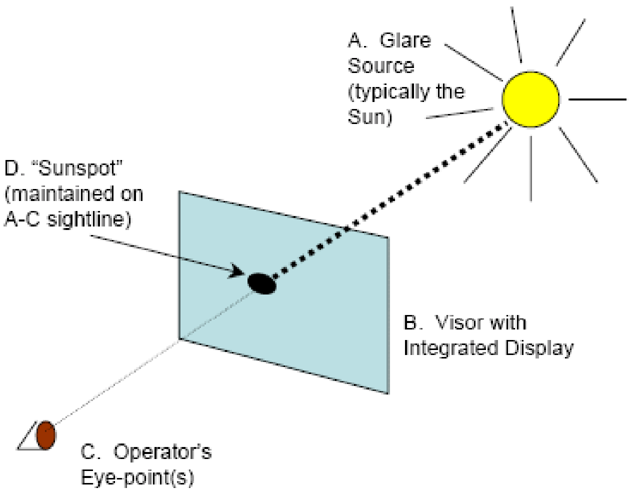

Figure 4. The dynamic visor concept.

SOLAR UMBRELLAS - A low-tech assist for lunar explorers would be aluminized plastic film stretched over light frames as reflectors. They could provide the dual function of glare reduction and shadow illumination.

A slightly higher-tech alternative would substitute thin-film photovoltaic material for the plastic film, thus allowing the umbrella to provide electrical power to the suit in addition to glare protection. The power could also drive hand-held or suit-mounted lights to illuminate shadowed areas, as shown in Figure 5.

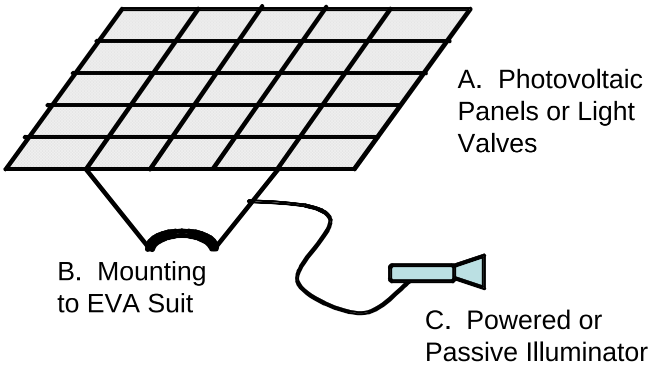

Figure 5. The solar umbrella concept.

POTENTIAL COUNTERMEASURES – TAKING AN ALTERNATIVE APPROACH

Thus far, we have only considered technologies that support direct viewing of the visual scene. But if ambient conditions overwhelm the accommodative abilities of our visual system, it may be useful to consider mediated viewing, whereby a processed image is presented.

As previously stated, the human visual system fairs better than most industry-standard equipment in terms of local adjustments to ambient lighting. But that performance advantage may soon vanish due to advances in image capture and processing technologies.

Commercial off-the-shelf (COTS) cameras are already available with 12 bits (3.6 orders of magnitude) of intensity. The imagery from such cameras could be displayed to astronauts in real time through head- or suit-mounted displays. These displays would be ordinary range displays to maintain constant adaptation level. Image processing would convert the high dynamic range images into ordinary range images. One possible strategy would be to use eye position monitoring to optimize the foveal region.

HIGH DYNAMIC RANGE CAMERAS – The newest generation of video camera achieve much higher dynamic ranges than have been realized heretofore, and may ultimately surpass that of the human eye. For example, the Atmel AT71XHD tri-CCD color line scan cameras advertise a robust casing and mechanics to withstand severe industrial environments. The high-sensitivity 3 CCD 1024 or 2048-pixel image sensors have 12 bits of dynamic range. The device features a data rate of up to 40MHz, and color separation that relies on prisms.

HIGH DYNAMIC RANGE IMAGES / DISPLAYS – Cornsweet and Yellott (5) developed an image processing technique that reduce dynamic range while spatially integrating the low photon count regions to reduce the effective photon noise. Image processing scientists have also developed methods for image modulation.

Figure 6. Local adaptation techniques can enhance image details typically lost in the shadows.

In Figure 6, the left image shows Paul Debevec's HDR photo of Stanford Memorial Church, using the technique of selecting the nearest available color on the monitor. The right image shows Fattal, Lischinkski, and Werman's (6) tone mapping algorithm, which uses a more sophisticated adaptive approach. You can see more details in the shadows and the highlights. Planning and training for lunar activities could be facilitated by high dynamic range displays of the simulated lunar surface. The Dolby BrightSide display (7) attains 16 bits of dynamic range using individually modulated LED backlights, thereby achieving 10X the brightness and 100X the contrast of standard monitors.

The high dynamic luminance range in the lunar environment suggests that mediated viewing may prove a useful mitigation. High dynamic range cameras and displays can extend the range for lunar explorers. Cameras can also, of course, increase the aperture to increased photon count (at the expense of increased lens size). Further, for smaller diffraction-limited blur, camera systems can extend the spectral range, narrow the spectral filtering, and (together with image processing) increase the duration of image capture to increase photon counts while removing motion blur.

CONCLUSION

Science-fiction author Robert A. Heinlein titled his book (8) quite accurately: the Moon is indeed a harsh mistress... especially with regards to ambient illumination. The lack of atmospheric attention and scattering creates extreme shadows and glare.

These challenges will be exacerbated in polar missions. It is therefore critical that we exploit the advances that have been made in electro-optics during the past four decades to develop new countermeasures that will ensure safe and productive EVA operations.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CANDELA: A standard unit of luminous intensity
CCD: Charged Coupled Device
EVA: Extra-Vehicular Activities
LCD: Liquid Crystal Display
UV: Ultra-Violet