Engineering Notes

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Moments Applied in the Rotation of Massive Objects in Shuttle Extravehicular Activity

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Introduction

DURING the Shuttle era of the U.S. manned space program, extravehicular activity (EVA) has demonstrated increasingly important capabilities. Building on this record of success, the Space Station era will likely incorporate EVA into routine operations involving the assembly of truss and platform structures, servicing of station subsystems, attached payloads, satellites and upper-stage vehicles, and experimental support involving retrieval and replacement of modules. Although much effort has gone into providing adequate life support and restraints for EVA crew members, there is little quantitative understanding of the performance of useful physical work in weightlessness. Critical EVA tasks upon which entire missions may be based can remain highly speculative until they are attempted. An important class of such critical EVA tasks is the manual handling of large and/or massive objects. Underwater neutral buoyancy simulation, the current standard for EVA crew training and important in establishing the feasibility of hypothetical EVA tasks, is particulary susceptible to hydrodynamic biasing for such tasks. A quantitative data base addressing the manual handling of massive objects in EVA is needed. The present paper reports experimentally derived applied moments for rotations of massive objects for Shuttle EVA missions. The relevance of applied force and moment as a manual handling task metric has been discussed elsewhere.[1]

Motion Analysis

Of the eight Shuttle EVA missions to date, three have involved significant handling of objects with comparable or greater mass than human body weight. In two separate EVA's on mission STS-51A, crew members captured and berthed in the payload bay two malfunctioning Palapa and Westar satellites for return to Earth and servicing.[2] On mission STS-51I, a 6600-kg Leasat satellite was manually captured, repaired, and deployed.[3] On mission STS-61B, crew members manipulated both the EASE and ACCESS truss structures.[4] (Manual handling performance in the assembly of the EASE structure in a separate STS-61B EVA has been previously reported.[5]) Since accurate motion analysis was not a primary objective of these EVA's, only documentary videotapes were available as a data source for postmission analysis. The lack of either a fixed viewing format, a knowledge of camera parameters, or an appropriate background made standard techniques for the analysis of time-varing imagery inapplicable.

A simple technique tailored to the problem of reconstructing three-dimensional object trajectories from a sequence of two-dimensional camera images with little knowledge of camera attributes was developed for this problem.[6] The technique assumes that a rigid triangle is fixed and in view on the object whose trajectory is to be reconstructed, as shown in Fig. 1. by estimating the field of view of the camera S, the radial directions to each triangle vertex (ψ,φ) are determined from measurements of the camera image (u,v).

$$\tan\psi_A - Su_A, \qquad \tan\varphi_A = Sv_A$$

With prior knowledge of the triangle side lengths, the law of cosines is used three times to develop a system of nonlinear algebraic equations for the radial distances r of the triangle vertices.

$$r_A{}^2 + r_B{}^2 - 2r_Ar_B\cos\theta_{AB} - AB^2 = 0$$
$$r_B{}^2 + r_C{}^2 - 2r_Br_C\cos\theta_{BC} - BC^2 = 0$$
$$r_C{}^2 + r_A{}^2 - 2r_Cr_A\cos\theta_{CA} - CA^2 = 0$$

$$\cos\theta_{AB} = \sin\psi_A\,\sin\psi_B + \cos\psi_A\,\cos\psi_B\,\cos(\varphi_A - \varphi_B)$$

The conjugate gradient technique is then used to iteratively solve for the three-dimensional position of each triangle vertex. The accuracy of the technique is adequate unless there is substantial uncertaintly in triangle side lengths or the triangle surface is highly oblique with respect to the optical axis. By repeating the process for a sequence of frames, using the results from one frame to begin the iteration for the following frame, a trajectory for the object in motion is reconstructed.

Frame sequences were chosen as those depicting rotational movements confined primarily to a plane, starting and stop-

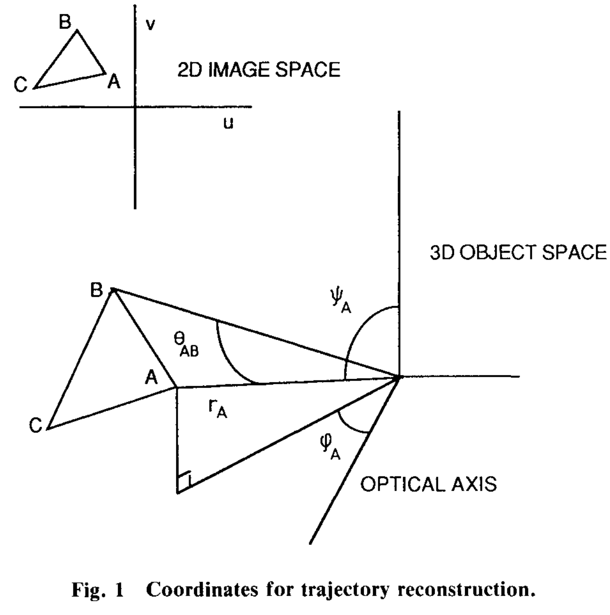

Fig. 1 Coordinates for trajectory reconstruction.

Received Dec. 16, 1988.

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Table 1 Shuttle EVA involving the rotation of massive objects

STS mission	EVA payload	Object being rotated	Moment of inertia I, kg m^2
61B	EASE	Single structural beam	120
61B	EASE	Assembled structure, about external axis	1,100
61B	ACCESS	Assembled structure, about internal axis	1,500
51A	Westar	Satellite with stinger, MMU, EMU attached	4,800
51I	Leasat	Satellite	45,000

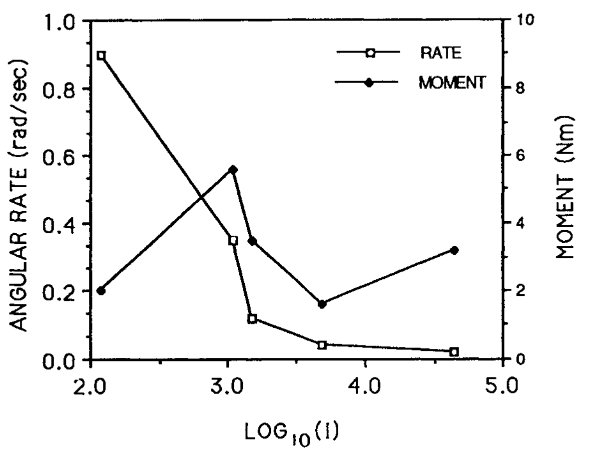

Fig. 2 Mechanical characteristics of the rotation of massive objects.

ping at rest. In each case, the EVA crew member performing the task was adequately restrained at the feet. No apparent motion or zooming of the camera was allowed. An object of known size a known distance from the camera must have been present to estimate the camera field of view. The resulting data set obtained from the available videotapes is summarized in Table 1. A rigid triangle was located on the object being rotated using identifiable features such as structural joints and corners. Size and mass properties were obtained from readily available mission documentation. Average angular rate was extracted by means of a sinusoidal fit to the trajectory. The appropriate moment of inertia I of the object being rotated was used to estimate the moment applied by the crew member to complete the movement. Although the calculation of applied moment is straightforward to tasks performed in EVA, hydrodynamic effects greatly complicate matters in neutral buoyancy simulation. No neutral buoyancy tasks were included in this study.

Results and Conclusions

The reconstructed angular rate and corresponding applied moment for five manual-handling cases identified earlier are shown in Fig. 2. The data indicate that as the moment of inertia of the object being rotated is increased, the angular rate is decreased so as to keep the applied moment relatively constant. This trend is demonstrated over nearly three orders of magnitude in moment of inertia. The applied moment averaged over all cases is 3.2 ± 1.6 Nm.

Because of limitations in both the amount and precision of the data, only preliminary conclusions can be supported. The relatively constant level of applied moment observed here indicates that applied moment is a reasonable determinant of purely rotational manual handling tasks performed by a foot-restrained EVA crew member. In the 1-g environment, metabolic energy expenditure is frequently used to characterize the physical workload of repetitive manual-handling tasks. In terms of the data presented here, mechanical energy expenditure is the product of angular rate and applied moment. Over the range of manual handling tasks in the present study, energy expenditure does not appear to be as consistent a quantity and, thus, not as useful a task determinant as applied moment. This conclusion does not alter the fact that over extened time durations, metabolic energy expenditure must be considered to insure adequate life support capabilities.

The levels of applied moment observed in operational EVA appear to be small fractions of the corresponding physiological limits. Horizontal and vertical shoulder strength limits of greater than 50 Nm have been established for foot-restrained pressure-suited subjects in simulated weightlessness.[7] The reduced level in operational EVA is perhaps due to an unfamiliarity with manual control in true weightlessness, an effect that is not well simulated by neutral buoyancy training. It is, therefore, conceivable that for highly repetitive manual handling tasks such as extensive truss structure assembly, the natural learning process would result in significantly larger applied moments and correspond faster task completion times.

Acknowledgment

This work was supported by Contract NAS9-17266, "Biomechanics of EVA," from NASA JSC.

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Mars Tethered Sample Return

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Introduction

ONE of the highest priorities in planetary science is obtaining samples from other planets in the solar system. Mars ranks high on the list of bodies proposed for sampling. Present concepts for obtaining samples from Mars center entirely on lander vehicles. Missions based on lander vehicles

Received Dec. 16, 1988; revision received Feb. 20, 1989.

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