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Tethered Elevator Design for Space Station

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This paper describes the conceptual engineering design of a space station elevator that operates on a 10-km tether spanning the distance between the space station and a tethered platform. The unmanned mobile structure provides access to residual gravity levels, remote servicing, and transportation to any point along the tether. Design requirements including torque and power requirements are discussed. A configuration is proposed including the robotics, drive mechanism, and power generation and transmission subsystems. Design emphasis is placed on the hooking/unhooking of the tether and the conception of a suitable capture and drive mechanism to interface with the tether to control elevator motion. A brief discussion of the decison matrix analysis is provided to indicate the method used to select the chosen tethered elevator and subsystem configurations. The tethered elevator design illustrates the uses of such a device for space station operations.

Nomenclature

C_F = coefficient of friction, lb·s/ft
D = drive wheel diameter, ft
G = gravitational constant of Earth, $ft^2 \cdot lb/slug^2$
I = drive wheel mass moment of inertia, $slug \cdot ft^2$
M = mass of Earth, slugs
m = mass of the elevator, slugs
R = radius of tether orbit measured from center of Earth, ft
R_C = drive wheel radius, ft
T = torque, ft·lb
Y = radial distance from center of orbit, ft
$\dot{Y}$ = velocity of elevator relative to tether, ft/s
$\ddot{Y}$ = acceleration of elevator relative to tether, ft/s^2
ω = angular velocity of tether system, rad/s

Introduction

THE idea of tethers in space dates back to 1895 when Tsiolkovsky suggested connecting large masses in space by a long string to exploit weak gravity gradient forces.[1] As the idea is now reaching technical maturity, tethers can be used in innovative ways for an increasing number of applications.

Two main critical areas have been recognized by Merlina.[2] The first is the hooking/unhooking of the tether and the second is conception of suitable capture and drive mechanisms to interface with the tether and control elevator motion. Each of these areas is addressed and a design is suggested in this work.

With the advent of a permanent presence in space a number of new operating environments will be introduced. The Space Shuttle will be required to dock on the space station to accomplish resupply missions. It will be necessary to develop procedures to minimize disturbances to sensitive experiments in progress on the station as the Shuttle docks and unloads. If the Shuttle were to dock and unload at some distance from the station on a tethered mass, and transport the cargo to the station via a tethered elevator, disturbance to the station could be reduced. If the tethered mass were below the station, Shuttle fuel would be saved. The elevator could also transport substances such as refuse requiring orbital deboosting.[2] This is accomplished by lowering the elevator along the tether to a predesignated position and then releasing the transported item. Decreasing the tethered mass has the advantage of transferring momentum to the space station and boosting its orbit, with no expenditure of fuel.[3]

Use of the elevator as a remote laboratory to access and control the gravity acceleration level is one of the most promising features offered by the system. By precisely positioning the elevator near the center of gravity (c.g.) on a tether system of fixed length, a minimum gravity acceleration level of 10^{-8} could be attained.[2] Scientists would then be able to take advantage of residual gravity levels, as well as the clean environment provided by a remote laboratory in space.

Another useful potential exists for the elevator as a remote servicing vehicle. If repairs were needed on a tethered mass such as a spacecraft or satellite, the elevator could be deployed to provide assistance. The provision of robotics onboard the elevator would enable manipulation of various articles such as mechanical and electrical umbilicals and orbital replacement units (ORUs).

Tether technology has not been fully tested in the space environment. The Tethered Satellite System (TSS) missions will be valuable in determining system feasibility. A TSS flight will be significant as a means of validating mathematical models and describing the dynamics, control, and key design factors for a tethered system and its components.[2] The tethered elevator is one component of this system.

Design Considerations

A primary design issue is the dynamic disturbance caused by elevator motion. If uncontrolled, adverse effects to the acceleration environment of the space station or the tethered object may result. These disturbances may act laterally or longitudinally with respect to the tether. Lateral vibrations are induced by the Coriolis acceleration, the drive motor, and the linear actuator, which will act on the elevator as it moves along the tether. The Coriolis force depends on the magnitude of the

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elevator's velocity and is as controllable as the velocity is small.[2] Longitudinal modes of vibration act on a line through the tether axis. These vibrations are due to control forces exerted from the elevator to the tether while accelerating or decelerating. The longitudinal modes have short periods in the axial direction and should be easiest to control.[2] The overriding consideration is the elevator's velocity. To minimize Coriolis effects the velocity of the elevator will be constant and not greater than 5 m/s.

In addition to control forces induced by elevator motion, the directional gravity acceleration along the tether will act on a line through the elevator's center of mass (c.m.), assuming radial and colinear placement. This gravity acceleration level can range from 10^{-8} at the c.g. of the tethered system to as high as 10^{-3} at a tethered body.[1] The combination of drive and gravity acceleration forces could induce moments on the elevator causing additional longitudinal vibration in the tether. Drive forces, however small, will always contribute to disturbances acting longitudinally, but moments created by an offset c.m. can be controlled by the elevator design.

Elevator mass and volume influence cost, stability, and tether life. Minimizing elevator mass and volume is a goal because 1) launch costs are great and increase with increased payload mass and volume, 2) mass moments of inertia about a small mass tether are minimized, and 3) tether life is preserved by minimizing drive forces and frictional effects applied to the tether.

The allowable tension in the tether is a factor limiting acceleration of a fixed mass elevator. If the drive mechanism produces a force greater than the allowable tension in the tether, slippage or deformation of the tether is likely.

Required critical analysis of the hooking/unhooking operation of the elevator by means of an Orbiter's Remote Manipulator System is essential.[2] The driver mechanism must be located in a position providing easy tether access to minimize time required for the attaching or detaching maneuver. In addition to the easy access requirement, the driver mechanism needs to be shielded from the space environment when the elevator is attached to the tether.

Robots aid in hooking and unhooking operations, manipulation of equipment, and servicing of tethered masses. The robot subsystem should be located to provide maximum access

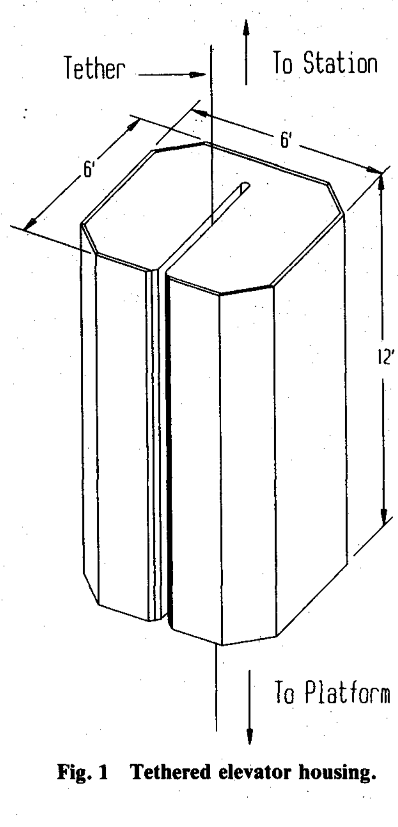

Fig. 1 Tethered elevator housing.

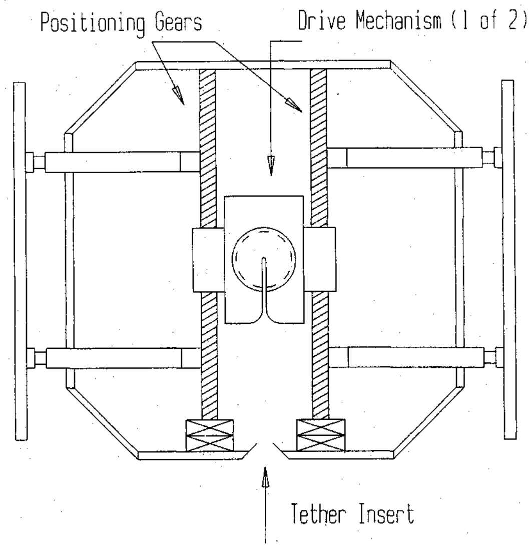

Fig. 2 Horizontal positioning mechanism (top view).

to equipment both on and off the elevator. The velocity of the elevator system with respect to the tether will need to be zero when the robotic subsystem is in operation.

The independent power generation and transmission subsystem will power the drive mechanism, the robotics, and the computers located on the elevator. The elevator's total power requirement, the mass of the power source, and the volume occupied by the power source are important factors considered in this design.

Proposed Configuration

Four areas of importance were tasks for the design of the tethered elevator. The design of the elevator structure was a critical task that affected each of the other tasks. Subsequently, three major subsystem design tasks were undertaken. Robotics, drive mechanisms, and power generation and transmission were the three subsystem tasks. In each task a number of alternatives were evaluated and a solution selected.

The structural configuration of the elevator selected consists of a main unit, component shielding, a horizontal positioning mechanism, and a counterbalance mechanism. The main unit houses, supports, and protects all subsystems and mechanisms onboard the elevator. The main unit shape, dictated by internal component dimensions, is an elongated octagon as shown in Fig. 1. The octagonal envelope provides sufficient surface for the many unique hardware mounting and internal fixture requirements. The four chamfered edges of the octagon were incorporated to minimize stress concentrations inherent in a rectangular structure. In addition, these edges, angled at 45 deg, eliminate sharp corners that may otherwise be unsafe for astronauts during extravehicular activity.

Shielding the main unit will protect and isolate internal components from the extreme temperature fluctuations present during Earth orbit. Additional protection is included to safeguard against atomic oxygen and micrometeoroid impact.

A horizontal positioning mechanism offsets moments created by an uneven mass distribution on the elevator. A counterbalance mechanism acts in conjunction with the horizontal positioning mechanism to insure the c.m. of the elevator coincides with the tether axis. Both mechanisms work together to maintain elevator balance.

The elevator or its payload must be moved relative to the tether to offset elevator mass moments. The horizontal positioning mechanism moves the elevator, whereas the counterbalance mechanism reconfigures the elevator payload. Horizontal positioning is accomplished with two worm gears as shown in Fig. 2. Actuated by computer software, these worm gears rotate and simultaneously position both the tether and

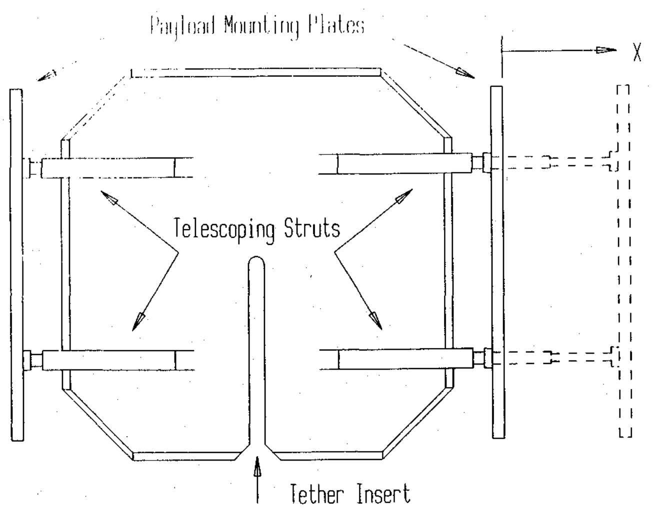

Fig. 3 Counterbalancing system (top view).

the drive mechanism to the desired location. Because the tether is being moved within the confines of the elevator housing, a stationary slot is part of the housing design. The slot allows the tether and drive mechanism to move with respect to the elevator. Also, the slot is used to funnel the tether into the drive mechanism when the elevator is hooked to the tether.

The counterbalance mechanism contributes to management of the c.m. by extending a series of telescoping struts that connect the elevator payload to the elevator structure as shown in Fig. 3. Telescoping struts are structurally rigid, provide sufficient c.m. movement, and take up small volume within the elevator. The rigid plate on which the struts and the payload are attached moves with the payload during extension and contraction.

The tethered elevator is designed to provide transportation and support for a wide range of Shuttle payloads. For this reason, the Shuttle-based pallet was used in this design as shown in Fig. 4. The pallets flown on the Shuttle are designed to secure support equipment and experiments. The use of the Shuttle pallet is therefore attractive for transporting and housing many types of tethered elevator payloads.

Robotics

The elevator will provide a means of transporting experiments, materials, and supplies to any point along the tether. With robotic implements affixed to the elevator structure these tasks can be accomplished more efficiently. The Tethered Elevator Remote Manipulator Subsystem (TERMS) assists in mechanical manipulation of a tethered object such as a Space Shuttle pallet as shown in Fig. 5. It is also useful in attachment and detachment operations between the elevator and the tether. The robotic implements can provide mechanical linkage between the elevator and any object located on a tether. End effectors located on the manipulators provide a means of securing or servicing a broad range of devices. Manipulators, in use or under development, were evaluated to gain insight into reasonable expectations for performance in space applications.

The proposed design consists of two diametrically opposed arms which are 1:3.5 scaled versions of the Shuttle's Remote Manipulator System (RMS). The Shuttle RMS has been used successfully in the space environment and has features making it desirable for elevator implementation. The TERMS arms are approximately 14.4 ft long and both are three-jointed arms possessing 6 degrees of freedom. The arms perform in space while anchored to the elevator structure. A standard end effector attaches to each wrist and is used for grappling, releasing, or applying force or motion to a payload.[4] The capture mechanism is comprised of three cables that close around a standard grapple fixture.[4] The manipulator arms, when equipped with a standard end effector, are capable of capturing a payload with a large misalignment and are dextrous enough to position a payload relative to the elevator's longitudinal axis with precision.[5]

Mechanical and electrical elevator interfaces, end effectors, man-machine interfaces, control techniques, and drive methods were investigated in the manipulator design. Fixed mount, quick change mount, and track drive designs were considered for the mechanical elevator interface. The electrical interfaces considered were coaxial cone and multipin connections. End effectors evaluated were snare type, parallel jaw, and multiple finger designs. End effector tool types considered included multiple arms and grippers. Control techniques using teleoperation, telerobotics, and autonomous control were evaluated. The man-machine interfaces considered were master-slave, joystick, exoskeletal, and helmet-type controls or displays. Drive methods evaluated were electromechanical and digitally driven servomanipulators.

Design analysis resulted in the following selections for the TERMS: fixed mount elevator connection, standard snare type end effector, two-arm end effector tool, Langley intelligent gripper, joystick interface, exoskeletal drive control, and a telerobotic control system.

Selection of computer hardware and data-transfer devices completed the design of the robotic subsystem. The IBM AP-101 general purpose computer was chosen to coordinate elevator functions. Reasons for selection of the IBM AP-101 include physical dimensions, space worthiness, and reliability. Five IBM AP-101's are currently employed aboard each Space Shuttle, handling a variety of tasks. System reliability is enhanced, since the IBM has a 95% detection rate of hardware

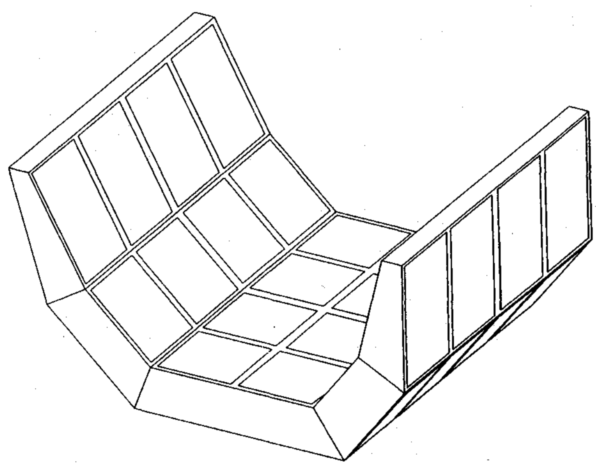

Fig. 4 Space Shuttle pallet.

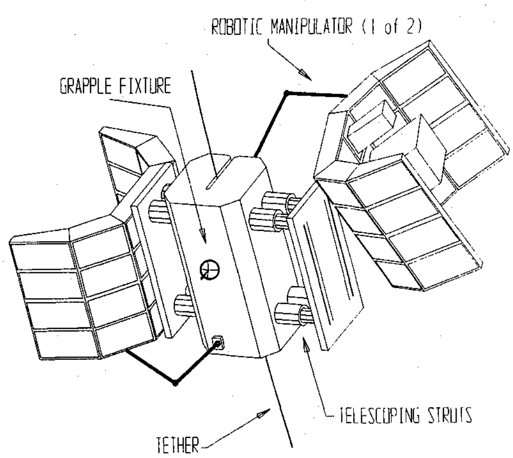

Fig. 5 Tethered elevator and RMS.

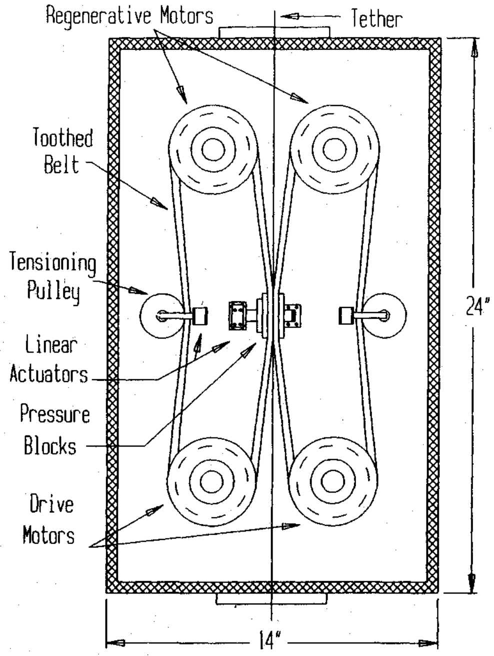

Fig. 6 Drive mechanism (side view).

failure. When hardware failure is detected, the system switches automatically to a backup unit. This feature, plus the proven service aboard the Shuttle, make use of the IBM AP-101 an attractive choice for the tethered elevator.

Since the tethered elevator is designed to operate as a remote vehicle, a data-transmission technique was chosen to relay computer commands to the elevator system. Packet radio transmission has been chosen as the best available data link between the space station and the tethered elevator. Packet radio techniques represent an evolution of wireless message switching methods. Data information is assembled in short messages (packets) that are transmitted to a remote destination. Electromagnetic transceivers would be mounted on the elevator and the space station. At microwave frequencies, relatively small antennas, on the order of 1 m in diameter, are capable of directing energy in the form of electromagnetic waves into narrow beams of a few degrees of divergence.[6] This is important for TERMS since the intended coverage extends the full length of the tether.

Drive Mechanism

The elevator drive mechanism design determines the mobile transporter's ability to traverse a tether in space. The drive mechanism selected as the chosen design was the bi-wheel friction belt as shown in Fig. 6. Two such drive mechanisms transmit power to propel the elevator. The same basic operating scheme as the tri-wheel friction belt, designed by E. Turci,[7] was used. However, several changes were incorporated in the bi-wheel friction belt to improve reliability and performance for unattended operation in the space environment.

The bi-wheel friction belt has two endless toothed belts that make direct contact with the tether. Considerations when selecting materials and coatings for these belts include long life with minimum outgassing rate when operating in low Earth orbit. The belts each operate on two pulley wheels. One wheel is driven by a torque motor and the other wheel is idle. When torque is applied to the drive motor, the belt is set in motion and the contact between the belt and the tether enables the elevator to move along the tether.

Two reversible, direct-current, shunt-wound motors with field resistance control drive the two friction belts to propel the elevator along the tether. The motors are designed for a considerable range of speed adjustment.[8] Each motor incorporates an automatic starter control to regulate the amount of current supplied to the motor. Automatic controls are necessary for the electric motors so that smooth acceleration may be obtained during frequent starting and stopping.[9]

Tachogenerators control the speed of each drive motor. A tachogenerator consists of a small, permanent-magnet type generator coupled to a motor's rotating shaft. The resultant voltage induced on the motor's armature coil is directly proportional to the speed of the shaft. The tachogenerator receives this voltage signal and, through the use of a feedback loop to the drive mechanism's control link, controls the motor speed.

The bi-wheel friction belt drive mechanism uses a synchronous belt to control creep. A synchronous belt is a toothed belt that merges with a toothed pulley during operation, thus eliminating slip by transmitting power through positive engagement. Synchronous belts have advantages over gears and chains. They can reliably transmit high loads with low noise, without lubrication, and the shock absorbing characteristic of the rubber teeth against a metal pulley is beneficial. In addition, the static tension of a synchronous belt is less than V-shaped and flat belts. The resulting lower preload on shafts and bearing reduces starting load, allowing use of drive motors with lower starting torque.

The synchronous belts are toothed only on the middle one-third of their width. The continuous belts are 47 in. long and 2.67 in. wide. The primary interface of the toothed portion of the belts is with the drive pulleys while the primary intérface of the smooth portion of the belts is with a flat plate. The plate is self-lubricating, contains no moving parts, and maintains constant pressure over the entire surface area of the pressure block. It is attached to a linear actuator that maintains proper pressure on the toothed belts and tether. The tether is positioned in the middle of the belt. The friction between the pressure plate and the drive belts is minimized, using DuPont's Delrin 500AF, a material which is nonwearing and has a low coefficient of friction.[10]

A torque transducer assembled on each drive wheel measures the dragging force to provide proportional control of pressure block pushing force. The transducer converts change in pulley wheel torque to a signal that adjusts linear actuator pressure force through a feedback loop. Shortly before slipping would otherwise occur, the torque transducer commands the linear actuator to increase pressure block pushing force.

Braking of the elevator is accomplished by a rotor/caliper combination similar to that used in automobiles. Rotors located at the ends of each drive motor shaft are grasped by calipers during braking. This proven design provides safety, controllability, and efficiency. The regenerative feature of the braking system is provided by four 1.7-hp dc, shunt-wound motors that act as generators during braking. The motors, connected to the two idle pulleys of each drive mechanism, convert rotational energy into electrical energy.

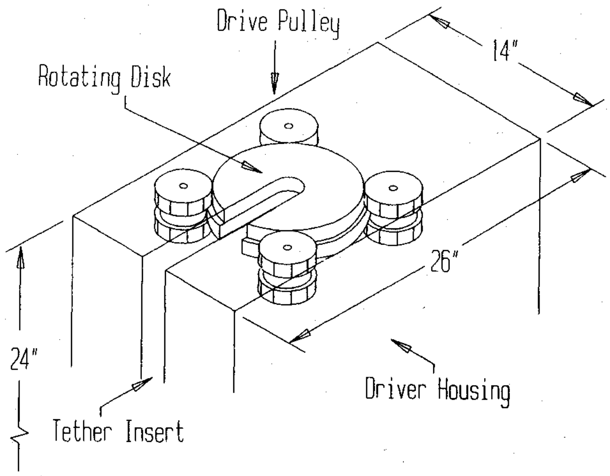

Fig. 7 Capture mechanism.

The housing for the two drive mechanisms measures 14×26 ×24 in. When the elevator is placed on a tether, Shuttle or station robotics mate with a standard grapple fixture on the elevator and approach the tether. At this point, the linear actuator of each driver is in the open position to insure space is available between the friction belts for tether insertion. The tether is then funneled by remote optics into a stationary guide slot and insertion between the pressure blocks is completed. Rotating disks affixed to the drive mechanisms now capture the tether by rotating 90 deg about the tether axis as shown in Fig. 7. When removing the elevator from a tether the inverse procedure is followed.

Torque and Power Requirements

The torque and power required of the drive mechanism varies with elevator and payload mass and distance from the c.g. The required torque is given by Swenson.[11]

$$T = \left(\frac{mD}{2} + \frac{2I}{D}\right)\ddot{Y} + C_F R_C \dot{Y} + \frac{mD}{2}\left[\frac{GM}{(R+Y)^2} - (R+Y)\omega^2\right] \tag{1}$$

The first term is the acceleration term; the second is a measured term due to friction; and the third term is a function of distance from the c.g. If the second term is assumed a constant 10% of total required torque, the approximate torque becomes

$$T = \left(\frac{mD}{2} + \frac{2I}{D}\right)\frac{\ddot{Y}}{0.9} + \frac{mD}{1.8}\left[\frac{GM}{(R+Y)^2} - (R+Y)\omega^2\right] \tag{2}$$

Torque and power profiles vary with the control law used. Swenson's basic control law[11] was used to calculate the required torque and power as functions of acceleration, elevator and payload mass, and distance from the c.g. Consider a combined elevator and payload of 40,000 lb located on the tether at the maximum distance from the c.g. With this mass at maximum control law acceleration and a velocity of 5 m/s, the maximum torque and power required are calculated using Eq. (2) as $T_{max} = 32.6$ ft·lb and $P_{max} = 5.8$ hp.

Elevator Performance

Four 1.7-hp, dc, shunt-wound motors provide torque and power to propel the elevator. At a maximum velocity of 5 m/s, the torque and power provided by these motors are 38.1 ft·lb and 6.8 hp, respectively. These exceed the required torque and power calculated in the previous section using Swenson's basic control law.[11] In addition, the starting feature of the shunt motor produces up to 125% of full-load torque. Thus, the motors are capable of providing maximum torque and horsepower requirements described by the basic control law. For small loads over short distances along the tether, two motors could be used with two motors held in reserve.

Power Generation

Since space station power is projected to be a critical resource, the elevator has been designed to include an independent, self-sufficient power system. Options considered for power generation include solar photovoltaic, radioisotopic, electrodynamic, and fuel cell systems.

Solar photovoltaic cells are attractive for use in space because they do not consume fuel or exhaust themselves, and they have no adverse effect on the surrounding environment. On the other hand, solar cells require surface area proportional to power needs. For the tethered elevator this is a major drawback. Whether panels are mounted on the elevator body or on externally attached wings, the required surface area and associated drag interferes with elevator operations. In addition, positioning of the panels of the elevator toward the Sun poses a major operational problem. In spite of the advantages of solar power for space applications, elevator requirements indicate that another means of power generation may be more suitable.

Radioisotopic power generators are compact, highly reliable, and capable of producing electrical power for extended periods of time. Through the careful selection of radioactive isotopes and energy converters, the problem of power generation in many space applications can be solved. For the elevator application, problems in the areas of human safety, heat dissipation, and power/weight ratios indicate that the radioisotope system is not a reasible solution.

A geomagnetic power generation system using an electrodynamic tether is a challenging, yet promising approach for an elevator power source.[12] This system uses a conducting tether traveling through the magnetic field of Earth, and ionic plasma to induce high voltage across the tether. Plasma-motor generators (PMGs) are used to promote contact with the ionosphere and ambient plasma so sufficient current passes through the tether. This closes the electrical circuit and provides power to the tethered elevator.

Four PMGs could be used in this design, one at each end of the tether and one at both top and bottom of the elevator structure. This configuration allows two separate circuits to be created. One circuit exists between the elevator and space station, and the other exists between the elevator and the tether end. As the elevator traverses the tether, the electrical potential varies with elevator position. Maximum power becomes available at the point of maximum power requirement since the voltage is proportional to the tether length.

The electromagnetic tether is particularly well-suited for the elevator because it enables maximum use of the elevator structure to fulfill its primary mission functions. The major disadvantage of a conducting tether is its lack of proven use. The basic principles have been shown, but converting the power and transmitting it to a device, such as the elevator, has not been demonstrated in space.

Fuel cells have been used as a power source on Apollo, Gemini, and the Space Shuttle Orbiters. Because of their small size and modularity, they can be configured to meet virtually any power requirement without sacrificing efficiency. Fuel cell power is continuous in nature, produces very little noise, and no noxious emissions. A fuel cell is a device that converts chemical energy of a fuel and oxidant into electrical energy. Since the conversion cycle is electrochemical, rather than thermal, fuel cells are not subject to Carnot cycle efficiency limitations.[13] Using fuel cells on the tethered elevator appears to be the best solution for the production of power.

The proposed fuel cell power system for the tethered elevator consists of a single power plant using three oxygen and three hydrogen tanks. The system is designed to provide 2-kW minimum, 7-kW continuous, and 12-kW peak power. The fuel cell stack accessory package handles reactant management, thermal and electrical control, and water removal. The accessory package is located at one end of the power plant stack and can be separated from the cell stack for easy maintenance.

The hydrogen and oxygen required for the fuel cell are cryogenically stored in a supercritical condition (97 K or −285°F for oxygen and 22 K or −420°F for hydrogen). For this storage double-walled Dewar-type tanks are used. The oxygen tanks are 7.87 in. in diameter and hold 183 lb of oxidant. The hydrogen tanks are 15.2 in. in diameter and hold 22.9 lb of fuel. Coupled together by a fuel regulator system, three hydrogen and three oxygen tanks provide 168 h of continuous operation.

Backup is provided by a secondary fuel cell. Fuel from the primary fuel cell is rerouted to the secondary fuel cell in case of primary fuel cell failure. In the event of regulatory valve failure, the secondary fuel cell is equipped with two emergency fuel tanks capable of powering the elevator to the station from any point on the tether.

Table 1 Elevator configuration study

Design parameters	Weight factors	Optimum design	Modified dual pallet	Modified component
Simplicity	9	17	14	12
Durability	7	17	17	15
SS disturbance	8	16	16	13
Internal storage	8	15	15	15
Mass	6	14	14	18
Maintainability	8	17	16	14
Accessibility	5	17	13	13
EVA requirement	7	15	15	13
Hook/Unhook	9	17	13	12
Performance	8	18	17	16
Transportability	7	18	12	13
Robotics	6	18	12	12
Reliability	9	15	15	15
Payload capacity	6	19	18	11
Stability	7	18	17	13
CM adjustment	8	17	12	12
Power	7	14	14	17
Feasibility	8	17	16	16
Cost	9	15	15	15
Shielding	4	18	17	13
Totals		2413[a]	2171	2034

[a]Chosen design.

The fuel cell power generation systems are backed up by nickel-hydrogen batteries. Nickel-cadmium batteries have traditionally been used as storage systems on spacecraft; however, the latest and most efficient battery configuration uses hydrogen in place of cadmium.

Method of Analysis

The chosen design of the tethered elevator configuration, including subsystems, was achieved by analyzing design considerations and parameters.[14] Using decision matrix theory, numbers from 0 to 20 were inserted into a matrix that relates each design consideration to individual design parameters. The parameters were given a weighting factor from 1 to 9 to indicate relative importance. The results are computed by multiplying the numbers in the matrix by the applicable weighting factors and summing vertically. This yields a numerical representation of each design with the largest number indicating the best design as shown in Table 1.

Summary

The chosen tethered elevator design presented displays potential for use on the international space station. Traversing a deployed tether of fixed length, the elevator could provide robotic support to tethered objects, exploit variable gravity levels for experiments, and generate its own power during the accomplishment of these tasks.

Evaluating the operation of the elevator in microgravity is the critical next step toward determining overall feasibility of the concept. Tether dynamics, elevator stability, and control of elevator motion are important areas for further study and experimentation in this spacecraft development.

Acknowledgments

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References

[1]Bekey, I., "Tethers Open New Space Options," *Proceedings of the Tethered Applications in Space Workshop,* NASA's Office of Spaceflight and MSFC, Vol. 1 of 2, NASA CP-2364, June 1983, pp. 1-18-1-30.

[2]Merlina, P., Bogo, W., and Ciardo, S., "Tethered Elevator and Pointing Platform Demonstrations: A Shuttle Flight Test of Scaled Engineering Models," *Advances in the Astronautical Sciences,* Vol. 62, NASA CP-2458, Sept. 1986, pp. 147–171.

[3]Ionasecu, R., and Penzo, P. A., "Space Tethers," *Spaceflight,* Vol. 30, No. 5, 1988, pp. 200–208.

[4]Daniell, R. G., and Sachdev, S. S., "The Design and Development of an End Effector for the Shuttle Remote Manipulator System," *Proceedings of the 16th Aerospace Mechanisms Symposium,* NASA, Washington, DC, May 13–14, 1982, pp. 46–48.

[5]Thring, M. W., "Manipulators with Memory; Remote Manipulators; Machine Limbs for the Handicapped," *Robotics and Telechirs,* Halstead Press, New York, 1983, p. 258.

[6]Feher, K., "Advanced Digital Communications," *Systems and Signal Processing Techniques,* Prentice-Hall, Englewood Cliffs, NJ, 1987, p. 10.

[7]Turci, E., "Tether Pointing Platform and Space Elevator Mechanisms Analysis of the Key Concepts for Science Applications and Tethered Platforms—SATP," *2nd Applications of Tethers in Space: Workshop Proceedings,* Venice, Italy, Vol. 2, NASA N86-27654, Oct. 1985, pp. 312–315,.

[8]Oberg, E., "Electric Motors," *Machinery's Handbook,* 21st ed., Industrial Press, New York, 1981, pp. 2348–2372.

[9]Avallone, E., "Shunt Motor," *Mark's Standard Handbook for Mechanical Engineers,* 8th ed., McGraw-Hill, New York, 1978, pp. 15–33.

[10]Anon., "Delrin," *Design Handbook for DuPont Engineering Plastics,* E. I. Dupont de Nemours & Co., Wilmington, DE, 1989.

[11]Swenson, F. R., "Tether Crawler System," NASA/ASEE Summer Faculty Fellowship Program, Marshall Space Flight Center, Huntsville, AL, NASA N87-16742, 1986, pp. 1–19.

[12]Vignoli, M., Miller, W., and Matteoni, M., "Power Generation with Electrodynamic Tethers," *Advances in the Astronautical Sciences,* Vol. 62, NASA CP-2458, Sept. 1986, pp. 473–481.

[13]Angrist, S. W., "Fuel Cells," *Direct Energy Conversion,* 4th ed., Allyn and Bacon, Needham Heights, MA, 1982, pp. 329–385.

[14]Anderson, L. A., and Haddock, M. H., "Matrix Design Analysis," The Space Station Tethered Elevator System, NASA/USRA Final Rept., Dept. of Mechanical and Aerospace Engineering, Univ. of Central Florida, Orlando, FL, 1989, App. B.

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