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LEO, LUNAR, MARS, AND ASTEROID PROJECTS

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SPACE HABITAT, ASSEMBLY AND REPAIR FACILITY

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Abstract

Integrated Space Systems (ISS) has designed a Low Earth Orbit Assembly Facility for submission in the 1992 AIAA/LORAL Team Space Design Competition. This facility, the Space Habitat, Assembly and Repair Center (SHARC), will be used to construct, assemble, and service space vehicles. SHARC's primary mission will be the construction of interplanetary vehicles, but it will also be able to perform repair and refueling operations of craft which are in an Earth orbit. This facility has been designed using only present and near-present technology, with an emphasis on minimizing cost.

Introduction

Integrated Space Systems (ISS) designed a Space Habitat, Assembly and Repair Center (SHARC) in Low Earth Orbit to meet the future needs of the space program. The goal is to meet the general requirements given by the 1991/1992 AIAA/LORAL Team Space Design competition with an emphasis on minimizing the design costs. During the spring semester of 1992, a baseline structural configuration was created along with preliminary designs of the major subsystems.

Assumptions and Requirements

The initial mission requirements were set by AIAA; the facility must be able to:

- support simultaneous assembly of three major vehicles
- conduct assembly operations with minimal EVA
- provide storage locations with easy access to work areas
- maintain orbit indefinitely
- assemble components 30 ft long with a 10-ft diameter in a "shirt-sleeve" environment.

The design team made the following assumptions to further refine the mission parameters:

- "Three major vehicles" were defined as two lunar vehicles and one Mars vehicle. For relative sizes, see Table 1.
- SHARC must begin limited operations after eight launches.
- No Heavy Lift Launch Vehicle (HLLV) of Shuttle-C will be available.
- The maximum crew size is eight and the maximum work tour is 35 days.
- A garbage collection system will be available to deal with orbital debris.

SHARC's baseline configuration design was based on the above requirements and assumptions.

Table 1 Interplanetary vehicle sizes

Vehicle	Total Mass (mt)	Fuel Mass (mt)	Maximum Diameter (m)	Length (m)
PhTV	1311.3	811.5	23.1	58.4
PhCV	467.0	262.8	18.8	43.1
MTV	n/a	n/a	27.4	8.3
LTV	94.1	80.9	13.7	6.9
LTS	191.7	159.2	15.2	22.9

Structural Configuration

Twelve different conceptual designs were reviewed; the chosen design is called the Hammerhead II.

The Hammerhead II configuration, shown in Figure 1, is composed of two 35-ft x 200-ft double deployable trusses separated by 4 35-ft erectable trusses. There are two smaller bays for lunar vehicles and one large bay for assembling the Phobos and Mars Transfer vehicles. A track system mounted by remote manipulator arms will encircle each bay allowing the arms to assist in vehicle assembly, hence minimizing EVA. There is a total of seven robotic arms to help in vehicle assembly: 1 30-ft arm for each lunar bay, 2 30-ft arms for the Mars bay, 1 30-ft arm for storage of parts, and 2 60-ft arms located on the sides of the main deployable trusses for berthing and transporting payloads.

A general storage area is located in the 21-ft x 50-ft x 35-ft area between the two double fold deployable trusses, making it easily accessible to all assembly bays. An alternate storage area is located on the double fold deployable truss leading out to the solar arrays, which is accessible by a robotic arm. The spring-loaded 31-ft x 14-ft-diameter Phobos fuel tanks will be located near the Mars bay ready to be jettisoned for safety.

The emergency escape pod is located in the center of the four habitation and control modules and is accessible from two pressurize corridors for quick use. The modules are arranged in a racetrack configuration to provide dual egress in case of emergencies. The two control modules will contain windows which will overlook the lunar bays to help in vehicle assembly and payload berthing.

The eight sets of solar arrays and the battery system are located at the end of the double fold deployable truss. The 40-ft x 20-ft pressurized sleeve, which is attached to the airlock, can contain a 30-ft x 10-ft component and is accessible to the robotic arms. Finally, the shuttle will dock upside down to the remaining airlock. This provides plenty of clearance for docking, and the Shuttle can be rigidly connected to the double fold deployable truss through attachment points in the Shuttle payload bay.

Orbit

It was determined that the orbit of SHARC should be at an inclination of 28.5 deg. and an altitude of 380 km. This altitude is accessible to all current medium and heavy lift launch vehicles in use with only minor reductions in payload capacity. The inclination angle was chosen because it provides an ideal transportation node for future Mars and Lunar exploration missions. This inclination can also be reached by rockets from both the Kennedy Space Center and Kourou. In addition, the ballistic coefficient of SHARC was determined by an accurate model. Included in the research was a scenario for utilization of the Space Station Freedom as a habitation depot for the workers on SHARC. However, calculations showed that the high synodic period of the two facilities imposed additional design requirements which would lead to an increase in cost and complexity.

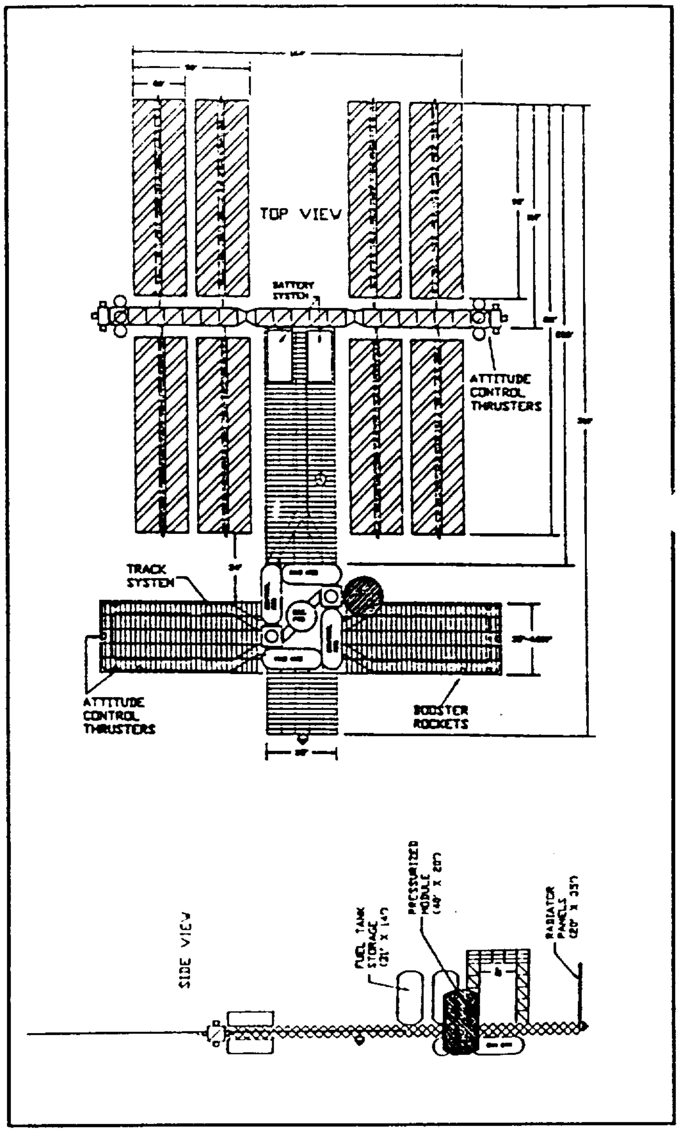

Fig. 1 The Hammerhead II configuration

Crew and Life Support

A work tour on SHARC will consist of a maximum crew of eight over a period of 35 days. The shuttle will stay docked at SHARC for the full duration of the mission. Each astronaut would work for 8 hours per day, 6 days a week. Life support supplies would be carried on the Shuttle. Any assembly materials will be sent to SHARC in an unmanned vehicle which would be launched 3 to 10 days after the Shuttle.

The Crew and Life Support group performed sizing estimates for a closed-loop life support system involving full air and water recycling. Further calculations were made involving specific supply requirements. Preliminary estimates revealed that 147 kg of nitrogen gas and 343 kg of food will be required for each work tour. 107 kg of methane and 183 kg of solid waste matter will be generated during the work tour and will have to be removed.

Power

The amount of power required to run SHARC was determined by considering the power requirement of each subsystem, and estimating power consumption of exterior flood-lighting for bays, robotics, power tools and EVA. This calculations resulted in a power requirement of 62 kilowatts. Assuming 10% line losses, the total power required is 68 kW.

Photovoltaic silicon solar arrays were chosen as the primary power system. It was determined that a total area of 1854 m^2 is required to provide the 68 kW of power. The arrays are arranged as eight pairs of fold-out panels which deploy along an erectable mast or boom for stability. The total mass of the arrays is 2267 kg and have a calculated lifetime of 10 years after which they will have experienced approximately 25% degradation in efficiency.

The storage system chosen to power SHARC during eclipse periods is composed of 27 Nickel-Hydrogen (Ni-H_2) individual pressure-vessel batteries connected in parallel for increased capacity and redundancy. The batteries are arranged together in groups and are placed in thermally controlled cases for optimum performance. The cases are placed between the two large sets of solar arrays. Each Ni-H_2 battery has a capacity of 100 amp-hours, an energy density of 25 W-hr/kg, and a mass of 112 kg. The total mass of the battery system (not including wiring) is approximately 3024 kg. For a worst case scenario, the batteries have a lifetime of 2 years if they are required to generate continuous peak power. Using a more probable average power of 48 kW, the lifetime will increase 5 to 6 years. After this time, the batteries will experience significant degrading and must be replaced.

Robotics

The construction and operation of SHARC will require the extensive use of robotics. The need for robotics stems from the hazardous nature that long-term EVA operations would present to astronauts and the need to relieve crew work loads. In addition, SHARC's main purpose of servicing space vehicles necessitates the use of robotics.

Two principal robotic systems were selected for use on SHARC: a remote manipulator system (RMS) and flight telerobotic servicer (FTS). These two systems are advanced versions of the ones to be used on Space Station Freedom. The use of robotic systems like these would reduce the uncertainties and costs in building SHARC.

On SHARC, the primary function of the RMS will be to capture and move large cargo to the assembly area. The FTS can attach itself to the assembly, or it can be an extension of the RMS, and proceed to work on light, precession assembly tasks. In addition, the FTS will be used to examine the structural elements of SHARC for maintenance purposes.

Guidance and Navigation Control/Reboost

The Guidance and Navigation Control (GNC)/ Reboost subsystem determined the propulsion requirements of SHARC during operation in space. Based on an accurate drag model, the propulsion system must be able to reboost SHARC from an altitude of 364 km to 380 km every two months. The total required ΔV was found to be 9.107 m/s. In addition, SHARC will be rotated 90 degrees during reboost periods, and there will be enough propellant stored to allow one additional reboost without resupply. The location of the attitude thrusters and the reboost thrusters is shown in Figure 1.

Propellants were compared on the basis of specific impulse and storage requirements. Hydrazine (N_2H_4) was selected for standard attitude control, while the reboost thrusters will use an OME/UR bipropellant (N_2O_4/MMH) rocket produced by Aerojet.

Communications

The communications subgroup used existing Space Station Freedom information as a basis for choosing the communication system for SHARC. Communications will be separated into a local system and a space to ground system. The local system will consist of an optical network because of its low power requirements and higher efficiency.

The maximum data rate for the local system is 10 Mega-bits per second (Mbps) with the option of using point to point fiber optics for a maximum data rate of 100 Mbps.

The space to ground system will consist of two virtual channels operating at a data rate of 150 Mbps. The frequency will be in the range of approximately two GHz to overcome any atmospheric or noise attenuation. The data will be transmitted to the Tracking and Data Relay Satellite System (TDRSS) and then to the Data Interface Facility which will allocate the data to the appropriate users. This link design will maintain continuous contact with the ground stations so that tracking and telemetry can be monitored.

Thermal Control

The thermal control group identified the different station elements that have specific operating temperature ranges; various passive thermal measures were studied to determine if they would be adequate to maintain the operating temperature ranges. This proved true in the case of the cryogenic fuel tanks. For the rest of the station, it was estimated that a peak load of 60 kW of waste heat must be dissipated. Therefore, an active thermal control system was designed using Freon-12 as a working fluid. A radiator panel 35 ft x 20 ft was found to be adequate for the thermal needs.

COMMON LUNAR LANDER

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Abstract

The Austin Cynthesis Corporation was formed to design a Common Lunar Lander (CLL) capable of carrying a lightweight (less than 500 kg), unspecified payload to the moon. The system could be utilized in further scientific study of the Moon by carrying payloads of scientific instruments custom-packaged for specific explorer missions. Additionally, it could establish and/or support a manned lunar base, through the transfer of small amounts of building materials, electronic equipment or other supplies. The Corporation has divided the task into three main parts: launch vehicle selection, lander design, and conceptual payload selection. Initial mass estimates led to consider a class of launch vehicles (including the Delta, Atlas, and Titan). The lander design itself has been divided into several subsystems: structures, power, thermal control, avionics, communications, and propulsion. Ideas for payloads include a common power system to satisfy various payload power requirements, a lunar experiment package, a materials utilization and testing platform, a surface rover, and a ground communications relay station.

Introduction

The Austin Cynthesis Corporation (hereafter referred to as "the Corporation") was formed to respond to a Request for Proposal for the design of a Common Lunar Lander (CLL) capable of carrying a lightweight (less than 500 kg), unspecified payload to the Moon. The Corporation believes that such a system could make a large contribution towards the continued progress of the civil space program. The system could be utilized in further scientific study of the Moon by carrying payloads of scientific instruments, custom-packaged, for specific explorer missions. Additionally, it could help establish and/or support a manned lunar base, through the transfer of small amounts of building materials, communications equipment, a lunar rover vehicle, or other supplies. Due to its unique design philosophy, the potential missions the CLL could perform will truly be limited primarily by the payload designer.

The RFP received by the Corporation required the contractor to evaluate all mission phases: Earth launch, lunar transfer, lunar capture, and descent to the lunar surface. Additionally, the contractor was required to design conceptually a variety of potential payloads which the lander might be required to carry. To fulfill these requirements, the Corporation has divided the problem into three main parts: launch vehicle selection, lander design, and conceptual payload selection.

Launch Vehicle Selection

Initial mass estimates led to the selection of the Delta, Atlas, and Titan class of launch vehicles. As the design progressed, mass estimates eliminated the Delta and currently available Altlas/Centaur as possibilities. However, planned upgrades to the Atlas/Centaur vehicle, to be ready by 1993, should comfortably meet the total mass requirement.

Lander Design

Structures

The lander design (Figure 2) has been broken into several subsystems: structures, power, thermal control, avionics, communications, and propulsion. The structures group has created a three-legged space frame design which provides for a two-meter diameter platform to which payloads will be affixed. This platform is hexagonal with diametric crossbeams. Small members may be connected between the main platform crossbeams to provide payload attachment points. The structure has been analyzed for particular static loads only; the short time available for the completion of the design precluded any attempt to perform dynamic modeling.

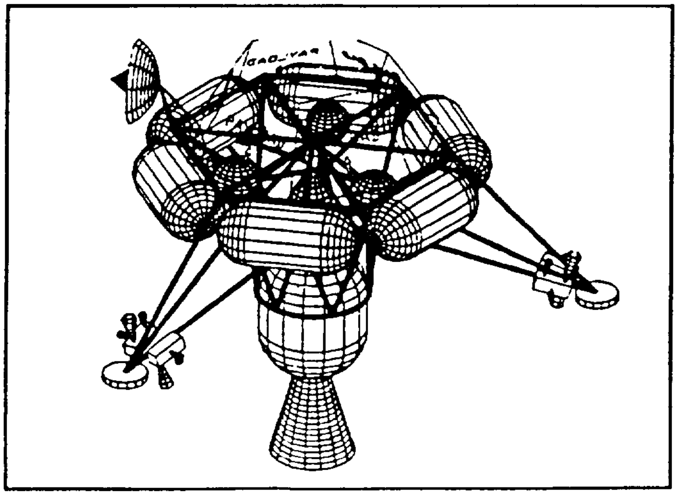

Fig. 2 Fully configured Common Lunar Lander

Power

Because of the short mission duration of the lander itself (its mission will end when it has reached the lunar surface), the power group has determined fuel cells to be the optimum power source. Other than offering a limited amount of startup power, the lander itself will not be responsible for powering the payloads. For payload power requirements, the possibility of carrying a "common" power supply module as additional payload has been investigated. It was determined that no system can exist which will use a standardized module to supply power to all possible payload configurations. However, it would be practical to develop a "family" of power supplies from which a "best fit" could be chosen for a particular mission .

Thermal Control

Thermal control of the lander will be accomplished using primarily passive systems to reduce weight and complexity. Spacecraft orientation, reflective paints, insulation, heat exchangers, and phase-change devices will be used to maintain the lander subsystems within their operational temperature ranges. Additionally, the structure of the lander itself can be used as a heat sink for the payloads, if required.

Avionics

The avionics subsystem will change significantly with payload mounting configurations. Therefore, the avionics must either be configured before each mission or else they must be adaptable for a range of lander and payload configurations. The pace of development of fully autonomous avionics systems indicates that an acceptable system would be available before the lander is scheduled to become operational.

Communications

The communications system is based on previous NASA explorer spacecraft. It is also shared between the lander and its payloads, as duplication of antennas, transmitters, and receivers is deemed unnecessary. It is expected that communications requirements for the payloads will be minimal during lunar transit, so that the lander will dominate communications use. After landing on the Moon, the lander itself will not require communications leaving the system to be used exclusively for payload needs.

C-4

Propulsion

The propulsion system of the lander consists of fine (25 N) and coarse (450 N) reaction control jets for attitude control, a solid rocket motor for lunar capture, and one storable bipropellant engine for deorbit, lunar descent, and landing. The fine control jets will be used for precision attitude maneuvers during free flight; the coarse jets will be used to compensate for moments about the center of mass of the spacecraft generated by the main engine thrust vector.

Payload Design

While the RFP has tasked the Corporation with the conceptual design of multiple payloads for the lander, the primary task is the design of the lander itself and most resources have been spent there. While several ideas for payloads have been advanced, time allowed for only a handful to be examined in any detail. These ideas include a common power system to satisfy various payload power requirements, a lunar experiment package, a materials utilization and testing platform, a surface rover, and a ground communications relay station. Other sample payloads which were proposed but not studied in this project included ground-based communications relay stations, families of transport containers (with options for power, pressurization, etc), modular building components, and a ballistic payload distribution system (to scatter small, shock-resistant items in an area around the lander).

Contents of Final Report

The Final Design Report Document includes information on (1) the requirements for the design project, (2) the ideas proposed as solutions to the design problem, (3) the work which has been completed in support of the design effort, justifications, (4) validations and verifications of decisions made during the project. A project schedule, including current status of the items included on the schedule, as well as cost and management summaries are also included. Finally, suggestions for future work to be done in support of the project have been written.

FAR SIDE LUNAR ASTRONOMICAL RESEARCH EXPEDITION

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Abstract

Lone Star Aerospace, Inc., has completed the preliminary design of a lunar observatory on the far side of the Moon. An observatory located on the far side of the Moon has many advantages over an Earth based observatory such as: (1) lower instrument weight due to the Moon's weaker gravity, (2) non existent atmospheric signal attenuation and filtering due to near vacuum conditions on the Moon, (3) sighting of the entire sky due to the slow rotation of the Moon, and (4) stability of the lunar surface which optimizes the use of large baseline instruments. The technical aspects of this project include site selection and precursory mission details, scientific instruments, communication, power systems, habitation and transportation, spacecraft design, thermal systems analysis, robotic systems analysis, and trajectory analysis. The site selection group focused its efforts on finding a suitable location for the observatory. Hertzsprung, a large equatorial crater on the eastern limb, was chosen as the base site. Two preliminary base designs have been developed. These two designs differ in the positioning of the larger instrument packages that will be placed on the lunar surface as well as in the type of habitat module that will be utilized.

Introduction

Lone Star Aerospace, Inc. (L.S.A.) has completed the preliminary design of a lunar observatory on the far side of the Moon. Such a base would not only establish a long term human presence on the Moon, but would also allow more accurate astronomical data to be obtained.

A lunar observatory is more desirable than an Earth based observatory for the following reasons:

- Instrument weight is reduced due to the Moon's weaker gravity.
- Near vacuum conditions exist on the Moon.
- The Moon has slow rotation to reveal the entire sky.

- The lunar surface is stable for long baseline instruments.

All the conditions listed above are favorable for astronomical data recording.

The site selection group focused its efforts on finding a suitable location for the observatory. Hertzsprung, a large equatorial crater on the eastern limb, was chosen as the base site.

Primary and Secondary Base Designs

Two possible base designs were developed. After analyzing these two designs, a primary base design and a secondary base design were selected. These two designs differ in the positioning of the larger instrument packages that will be placed on the lunar surface as well as in the type of habitat module that will be utilized. The primary base design consists of a main base with a Space Station Common Module (SSCM) type habitat and three large independent instrumentation fields - one separate field for the Very Low Frequency Array (VLFA), one for the Optical Interferometer (OI), and one for the Submillimeter Interferometer (SI). The secondary base, on the other hand, consists of a main base with an inflatable habitat and one large instrument field in which the fields for the VLFA, OI, and SI overlap each other.

The advantages of the primary base were analyzed. The main advantages of this base were as follows:

- Less interference between elements of the VLFA, OI, and SI.
- Easier placement and maintenance of the habitat.
- Easier expansion of any of the large instrumentation fields.
- Easier maintenance of an instrument element (since maintenance would not cause dust build up on nearby instruments as it would in the secondary base's overlapping instrumentation field).

The advantages of the secondary base were as follows:

- Less range required by transportation and robotics elements.
- Larger habitat.
- Less power and communications cable required to reach the instruments.

After analyzing these advantages and considering the fact that the main purpose of constructing the base is to obtain the most accurate astronomical data possible, the base with the SSCM and three independent instrumentation fields was chosen as the primary base. A sketch of the primary base is shown in Figure 3.

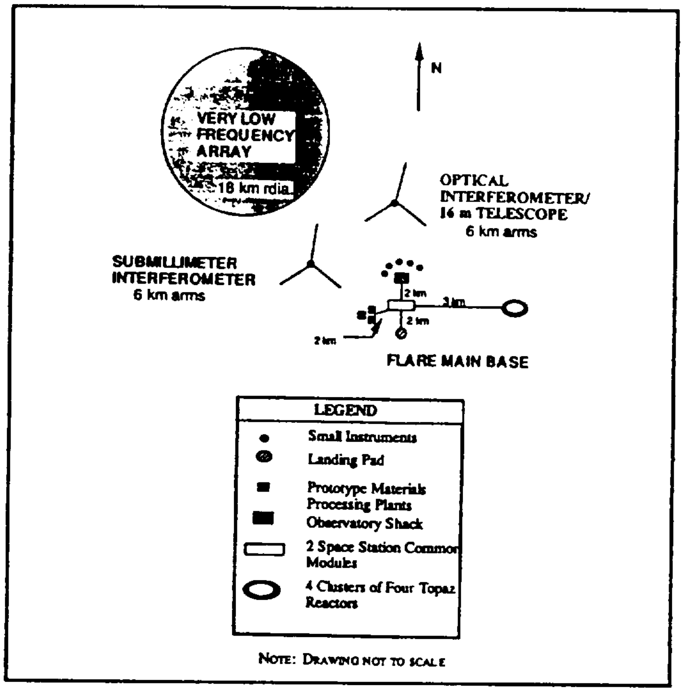

Fig. 3 Layout of the primary base

Overview of Subsystems

The design of the far side lunar observatory involved investigation into seven subsystems. These subsystems included instrumentation, habitation and transportation, power and communications, robotics, thermal systems, cargo spacecraft design, and trajectory analysis. The following sections give a brief overview of each of these subsystems.

Instrumentation

Astronomical, geological, and environmental instrumentation packages will be placed on the lunar surface. The following is a list of the major instruments to be utilized:

- Very Low Frequency Array,
- Submillimeter Interferometer,
- Optical Interferometer,
- Transit Telescope,
- 16 m Telescope,
- Moon-Earth Radio Interferometer.

The mass of the total instruments package has been estimated at 91 metric tons.

Habitation and Transportation

Two SSCM modules connected end to end will provide for habitation on the lunar base. Two airlocks at either end of this arrangement will provide adequate ingress and egress. A partially-closed environmental control and life support system will be utilized. MOSAP and LOTRAN vehicles will provide lunar transportation.

Communication and Power

During the construction phase, a satellite in an L2 halo orbit will relay data from the lunar surface to a geostationary satellite in Earth orbit to the Earth's surface. When the base becomes fully operational, however, a radio-free sky is desired to take accurate astronomical readings. Therefore, a fiber optic cable will be used as a communication link from the base to a transmitter/receiver station on the near side of the Moon. It will be laid out by a robotic rover from the base to the limb of the Moon. From there, the signal can be broadcasted directly to Earth without interfering with astronomical observations.

The base will be powered by four clusters of four Soviet manufactured Topaz reactors. These will supply the base with approximately 160 kWe of energy. Use of this cluster arrangement will prevent the total loss of power to the base in the event of a failure. If an emergency occurs and a cluster must be shut down, the other reactors can still produce 120 kWe for the base.

Robotics

Four robotic elements will set up the far side lunar base. They include a crane, an excavator/digger, and two assembly robots. They will dig holes, bury the habitation modules and reactors, lay power and communications cable, and set up the instruments. These robotic elements will use a combination of artificial intelligence and telerobotics to successfully navigate and construct the base.

Thermal Systems

The lunar base will be thermally controlled with the use of both radiators and heat exchangers. Radiators will be used to cool the reactors and heat exchangers will be used to cool the habitat and some of the smaller astronomical instrument packages. Manufactured shades will be used if passive cooling of the larger instrument packages is necessary.

Cargo Spacecraft Design

A cargo spacecraft designed by Eagle Engineering will be used to carry the 180 metric tons of materials from Low Earth Orbit to Low Lunar Orbit. A Lunar Operations Vehicle will then transport these materials to the lunar surface.

Trajectory Analysis

Cargo spacecraft trajectories will consist of spiral trajectory with a time of flight of approximately 130 days. Any manned missions to the base will use hybrid free-return trajectories.

Management and Cost

Lone Star Aerospace was composed of a project leader, integration leader, chief technical engineer, administrative leader, and seven technical departments (each with its own department leader). This type of management structure has worked quite efficiently. No major problems have arisen in the design of the far side lunar observatory.

A cost analysis on the design of the lunar base has been performed based on the hardware costs incurred over the past fifteen weeks as well as the number of man-hours utilized. These figures were then compared to the estimated cost for the project as presented in the proposal. The total cost for the design of this base has been calculated to be $51,853, well under the budget agreed upon in the proposal.

SYSTEMS INTEGRATION FOR MARS PLANETARY SURFACE OPERATIONS NETWORKS

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Abstract

A permanently manned Mars base will require a robust surface infrastructure to operate successfully. Frontier Transportation Systems (FTS) is designing a set of vehicles to meet the needs of such a base. The Systems Integration for a Mars Planetary Surface Operations Network (SIMPSONS) Project will support the following base operations: (1) exploration, (2) base expansion, (3) mining, (4) cargo transport (including fuel and interplanetary payload), and (5) personnel transport. The vehicles which make up the network will be land rovers, lifters, fixed-route transports, rocket hoppers, and aircraft. Modularity and ease of integration into the network will be emphasized in vehicle designs. For each vehicle, several conceptual designs have been developed along with a decision process for selection. The technical aspects of the design for each vehicle will be handled by groups devoted to vehicle subsystems. The subsystem groups are structures, power/propulsion, guidance and control, safety/life support, robotics, and communications. An integration group oversees these subsystem groups, ensuring that the vehicles meet their requirements as expected.

Introduction

Frontier Transportation Systems (FTS) has designed an integrated transportation network to support an advanced Martian base. The following paper represents the completion of the SIMPSONS project (Systems Integration for Mars Planetary Surface Operations Networks).

This project focuses solely on the surface-to-surface transportation at an advanced Martian base. Several elements, such as interplanetary transfer vehicles, orbiting nodes, and ascent/descent vehicles will be necessary for the sustenance of such a base. Any one of these components would be a significant project in itself; thus, they do not fall within the scope of the project.

Assumptions and Goals

FTS defined the SIMPSONS project with the following assumptions:

- Advanced Martian base exists.
- Transportation node in low Mars orbit exists.
- Supply route between LEO and LMO is available.
- Water is present on Mars.

In order to precisely determine the exact goals of our transportation system, the supported base needed a clear definition. FTS researched the most likely arrangements and locations of an advanced Martian base and selected a specific configuration. The base after which we modeled our system will be located at Utopia Planitia (30°N,240°W). Its favorable proximity to possible mining locations will facilitate the transport of raw materials to the base. Also, this latitude aids the ascent/descent vehicles by minimizing the plane change required to reach the orbiting transportation node which is at an inclination of 25°. Furthermore, this region is the largest flat area on Mars, which makes spacecraft landings, long distance travel, and communications easier. Finally, radiation shielding provided by the Martian atmosphere is increased at this location due to its low altitude (-1 km).

The following operations will be required of this type of advanced base:

- Mining of regolith for H_2O and O_2 to provide life support and fuel.
- Conducting scientific exploration and research.
- Expanding the base.

The base will accommodate a crew of 12 to 18 persons with the possibility of expansion. The main components of the base, shown in Figure 4, include the centrally located habitat area, a manufacturing facility, two nuclear power plants, two landing pads, and a garage/maintenance facility.

Surface transportation is needed for travel between some of the more distant elements of the base, as well as for mobility of crew and payload from one area of the base to another. Scientific expeditions require the use of both manned and unmanned transportation systems to reach distant sites of interest. Likewise, outposts such as scientific stations or mining sites need maintenance and replenishment of supplies. This can be accomplished by surface rovers or rocket hoppers. Closer to the base, raw materials must be delivered to the manufacturing facility for the production of necessities, such as oxygen and fuel, for base sustenance and maintainability. All of this requires a flexible transportation system, capable of transferring heavy cargo on a regular basis, and of transporting cargo over distances farther than the confines of the base.

Ultimately, the transportation system selected for the Mars base should be compatible with all payloads and should be adaptable to meet many tasks, including those unforeseen. Along with vehicles for the transfer of non-pressurized cargo, pressurized vehicles will also be needed for long range excursions. A transportation system composed of a set of modular vehicles which fulfills the needs of an advanced Martian base is presented in the final report. These vehicles include an aerial tram, a heavy lifter, a rocket hopper, Martian aircraft, and several different rover designs. This executive summary outlines the purpose and design of each vehicle, as well as recommendations for future analyses.

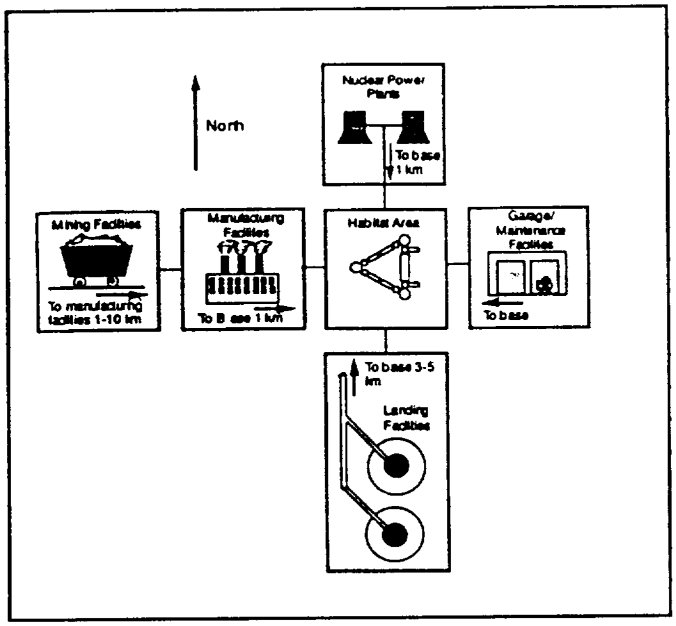

Fig. 4 General layout of the advanced Martian base

Aerial Tram

To support the mining operations of this base, it will be necessary to refine 216 MT of regolith per day. Upon analyzing the important aspects of a fixed route transportation system, FTS selected an aerial tram as the most efficient and economical mode of cargo delivery. The aerial tram is easy to construct, as it merely involves the setting up of two stations and intermediate trestles for support. In addition, the tram is easily automated, inexpensive to build and operate, and it requires little maintenance. The other fixed route types of transportation that were evaluated included trains, elevated rails, and magnetically levitated trains.

The aerial tram requires little mass to construct. The carriers are a simple automated design made of light-weight aluminum. The main mass to be concerned with, other than the payload chambers, is the weight of the hauling/carrying rope which will be made of a zinc-coated steel. The trestle mass should not be of concern, as the use of in-situ materials to form Martian concrete from which to construct these structures will eliminate the need to deliver the heaviest materials from Earth.

The tram we have designed will transport 36 MT per hour for the duration of only a quarter of a day. This will increase the lifetime of the system because it reduces the likelihood of fatigue and the opportunity for failure in general.

This system was a good choice from the perspectives of both the present and the future. From the present point of view, it can be constructed with the technology of today, and has proven to be a safe and reliable system on Earth. From a futuristic point of view, the aerial tram is an advantageous choice with regards to its ability to expand. First, the tram was designed to be strong enough to carry four times the amount it will actually be carrying. Thus it will be possible to increase its transport capacity in the future to support a larger crew. Secondly, the expansion of the base can be facilitated by first expanding the tram itself since it is possible to construct an additional route that is powered from the same driving station of an existing route. Finally, the tram may be used to efficiently transport humans in either pressurized or non-pressurized passenger cabins on future routes.

Heavy Lifting Vehicle

The lifter is designed to perform the loading and unloading processes within the base vicinity. This vehicle has to operate off of many platforms, ranging from the descent vehicle and the rover flatbed to the Martian surface. FTS will require that there be at least three lifting vehicles. One would be located at the landing pad, one at the base, and one extra should be present at any given time in case of mechanical failure. A crane design was chosen after evaluating forklifts and other lifting vehicles.

The crane must meet the following requirements:

- Maximum lifting capacity of 30 MT
- Capacity for cargo up to 6 m wide and 10 m long
- Total range of 10 km

- Fully telerobotic
- Flexible
- Durable
- Low maintenance
- Simplicity of design.

In our evaluations, we looked for the least massive crane which still satisfied the original requirements. Therefore, FTS selected trusses as the main lifting component to reduce weight. The selected crane, shown in Figure 5 is a composite of many Earth lifting vehicles. As shown, the crane has a horizontal truss and a vertical truss structure similar to the tower configuration of lifting cranes. The horizontal truss moves along the vertical truss in a forklift type movement. In the back of the crane is a large container which is filled with indigenous material to act as a counterweight. The horizontal truss has a maximum extension of about 10 m which provides flexibility in reaching the payload, and the vertical truss has a height of about 13 m. The grasping mechanism which hooks onto the payload can vary in position along the horizontal truss.

The crane is supported by a tracked wheel, which enables the crane to carry the cargo from one place to another. The empty weight of the crane was computed to be no more than 30 MT. By adding regolith as a counterweight, the total weight could go up to as much as 100 MT. The trusses and the grasping mechanism will be made mainly of aluminum alloy materials, which provide lightweight and high strength characteristics.

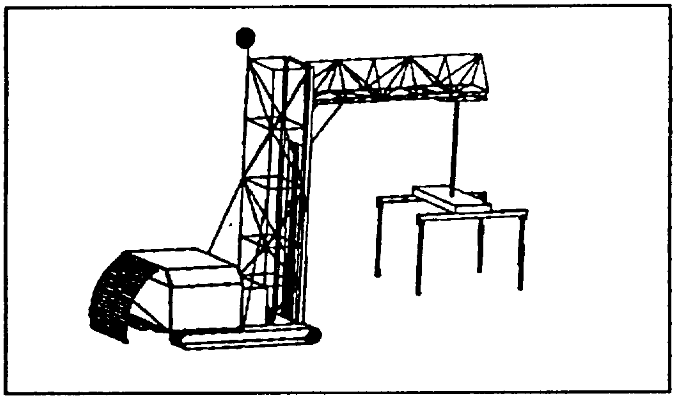

Fig. 5 3-D view of the Mars crane

The grasping mechanism has three degrees of freedom that can accommodate a maximum cargo width of 6 m. The lifter will get its power from a closed-cycle, internal combustion engine, using CH_4 and LOX for fuel and oxidizer, respectively. The lifter needs about 422 kW of power to travel 2 km/hr with a mass of 100 MT. The hoisting of the cargo using the grasping mechanism needs about 40 kW for a hoist rate of about 0.4 m/s. Also, the power required to translate the horizontal truss at a rate of 0.3 m/s along the vertical truss with 30 MT attached is about 50 kW. The crane will be controlled telerobotically by an operator from a command module located either in the habitation module or near the landing pad, where the majority of the loading and unloading processes will occur. To aide in telerobotics, the crane will need various sensors to accomplish the following tasks:

- Avoid obstacles
- Detect tilting of the vehicle due to uneven distribution of cargo mass
- Detect the range to the obstacle during loading and unloading processes
- Provide warnings of undue strains in support members.

Ballistic Martian Hopper

A ballistic rocket hopper provides a shorter transit time and a greater operating range. With a given payload of 6.5 MT, this vehicle can complete two missions: 1) carrying one autonomous rover with various scientific payloads, or 2) carrying a rover and a crew of two, with supplies for seven days. Our hopper can transport either payload to a site up to 1000 km from the base, where the small rover would then enable exploration within a 10 km radius around the landing site. Due to the fuel selection for our overall system (methane/oxygen), on-site refueling away from the base would not be feasible; thus the hopper is limited to one hop from and one hop to the base.

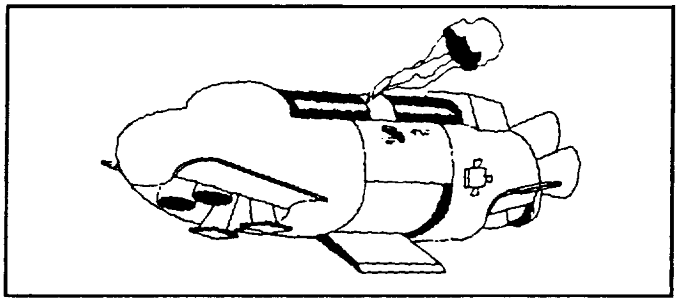

Fig. 6 Rocket hopper conceptual design

Figure 6 shows that the cargo bay was placed at the vehicle's center. The hover engines were then balanced around the bay in two equal, self-contained, and coordinated sets. This arrangement provides stability in firing and reduces shifting of the center of mass as fuel is consumed.

The trajectory of our craft was modeled by three phases -- launch, ascent, and touchdown. The launch is basically a hovering maneuver until the reaction control system (RCS) jets are fired to attain the proper attitude for the ascent phase. The main engines located at the rear of the vehicle are then fired for the ascent phase, sending the vehicle into a ballistic trajectory. When the hopper descends to 100 m altitude, a parachute is deployed.

The end result of our analysis consists of a partial load-bearing, functionally gradient material (FGM) skin supported by a graphite/magnesium interior structure. The skin is limited in its ability to bear loads by two main considerations. First, the engines of the undercarriage are recessed, and the ascent and descent thrust cannot be carried by the exterior skin. Also, there are several panels in the skin (clamshell doors, payload door) which would have to be carefully supported so as not to provide weak points in the structure.

Since the hopper must be able to operate autonomously and possibly telerobotically, its command and data handling system will have to be provided with information such as attitude, altitude, velocity and position, and surface mapping. The hopper will require an IMU capable of measuring the changes in attitude and position in three axes to fully define the state of the vehicle.

Unmanned Martian Aircraft

With the low martian gravity and despite the thin atmosphere, studies performed at the Jet Propulsion Laboratory in the late 1970's underlined that there were no technical difficulties involved in designing and operating a remotely piloted Mars airplane. It also appeared that such a vehicle could be most useful in increasing the capability of a Mars surface crew by providing for long range exploration and mapping.

The Mars airplane is well suited for long range scientific exploration, especially over rough terrain, and it can fulfill a wide range of missions such as surface imaging, atmospheric sounding, high altitude meteorology, and radio science. In addition, an unmanned Mars airplane can perform other useful functions such as deployment of remote observing stations, servicing of manned outposts, and search and rescue missions.

In order to enlarge the scope of operation, FTS evaluated both a large and a small aircraft. Because of the thin atmosphere and the need to keep aircraft dimensions and power requirements reasonable, the payloads of the aircraft need to be restricted. The large and small aircraft are restricted to 300 and 100 kg, respectively. The large aircraft has a range of over 12,000 km, and the small one has a range of 8000 km.

For both aircraft, a classical configuration was adopted since this configuration allows high lift-to-drag ratios and high stability. Moreover, the high tail volume can tolerate large shifts in the center of gravity resulting from payload deployment. Other features include an inverted V-tail to reduce mass as well as drag , high aspect ratio wings (22) in order to minimize the induced drag and large propellers for efficient high altitude flight in the thin Martian atmosphere.

Because of the composition of the Martian atmosphere (95% CO_2), only non air-breathing engines combined with propellers can be used. Because of its high power/mass ratio, a closed loop, internal combustion engine (CH_4/O_2) was chosen. In order to cut the total weight, an all composite structure was chosen, composed of high strength Thoronel 300 carbon-fiber and epoxy composites. This allows for a structural weight fraction between 15 and 20 %.

In order to minimize the take-off distance and thus the runway length, both aircraft are supposed to use a short-take-off device such as a catapult. The landing distance will also be shortened by using slow-down devices, such as nets. The landing gear for both aircraft will be a simple skid very similar to those used on gliders.

Like the rocket hopper, the small aircraft must have the capability to select a suitable site to land and to perform the landing autonomously. Nevertheless, the capacity to be remotely piloted should be available as an emergency back-up or for complex maneuvers. The computer will navigate mainly by a terrain-following procedure, using medium and high resolution images provided by previous or current remote-sensing satellites. The very high resolution images needed for high-precision procedures (vertical landings, for example) would have to be provided by previous aircraft missions. The command and data handling system could also rely on ground-based beacons for navigation. In addition, the avionics also need aircraft attitude, attitude rates, position, and position rates for navigation.

Rovers

The seven rover configurations which were designed for the SIMPSONS Project are: (1) fuel transport vehicle (FTV), (2) manned, short-range vehicle (MSRV), (3) materials transport vehicle (MTV), (4) Mars autonomous rover for ground exploration (MARGE), (5) human-operated Mars exploration rover (HOMER), (6) light cargo vehicle (LCV), and (7) heavy cargo vehicle (HCV). Table A shows the range and payloads for each vehicle.

Table 2 Ranges and payload masses for FTS Rovers

Vehicle	Range (km)	Payload (MT)
FTV	10	7.0
MSRV	30	2.2
MTV	30	7.0
MARGE	200	2.5
HOMER	200	10.0
LCV	200	2.5
HCV	20	10.0

The FTV will refuel the lifters, aircraft, and rovers, and serve as a backup to the pipelines that provide fuel for the hopper at the launch pad. The MSRV can be used for transportation in the base area, or it can serve as a short range exploration vehicle when included as payload on the hopper. The MTV is designed as a backup system to the tram. Since the transport of mined materials to the refining facilities is essential to life support, it is very important that we do not allow this operation to have a single point failure. MARGE will conduct autonomous long range unmanned exploration. HOMER will serve as a mobile lab for long range manned missions. The light cargo vehicle is an autonomous/telerobotic rover whose main purpose is the transportation of light cargo around the base area. The HCV, which will be operated telerobotically, will transport payloads of up to 10 MT within 20 km of the base to aid in such operations as base expansion by moving habitation modules from the descent vehicle to the base.

All of the components of the rovers should be modular. The advantages of this concept are that the modular blocks can be used as spare parts on almost any vehicle, and that new configurations can be made in-situ to meet unforeseen needs of the base. The astronauts will be able to construct (with robotic aid) any new vehicle configurations within the maintenance facility. The modular components were designed to fit on both a large and a small basic chassis design.

FTS selected hemispherical wheels as the mobility system for both the large and small chassis. The chassis was designed to be constructed of two-celled monocoque aluminum alloy beams. We selected a cell thickness of 5.0 mm for Al 2014-T6 beams after performing a static analysis of several different thicknesses and materials using NASTRAN.

For the purpose of commonality, the main power system for all vehicles with the exception of the rocket hopper and the tram were designed to run on a methane/oxygen internal combustion engines. This commonality in power source will facilitate maintenance of the vehicles and will also simplify the production of fuel since a common fuel is utilized. In addition, a modular concept (coined "legobility") designed for the rovers which employs the interfacing of various subsystem modules (black boxes) to configure a task-oriented rover (i.e. an unmanned autonomous rover or a manned mobile habitation module) is presented. This concept facilitates maintenance and also introduces redundancy into the system since spare parts are more readily available when needed. All these vehicles, when working together, will provide the support required for the sustenance of the advanced Martian base and indirectly, will lead the way to the settlement of Mars.

Recommendations

Due to the time frame and scope for which this project was undertaken, further analyses of each vehicle and its subsystems should be performed. Although this project gives an overall design for each of the vehicles which will be included in the integrated Martian transportation system, future studies will be required to develop these vehicles beyond the preliminary design stage. For further design of the tram, we recommend an analysis for reliability, and we recommend further research into the feasibility of using indigenous materials for the construction of the trestles. For future studies of a Martian lifting vehicle, we recommend a more detailed structural analysis of the grasping mechanism and the analysis of truss stability. For the hopper, the following areas must be studied further in order to achieve a complete vehicle:

- Vehicle lift-to-drag ratios
- Materials research/analysis
- Aerobraking
- Thermostructures
- IMU calibration.

The Martian aircraft needs further analysis in its thermal system, state estimation, takeoff and landing and artificial intelligence for surface terrain following. A dynamic analysis is required for further studies of the rover, as well as a more in depth analysis of the engine performance characteristics.