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ORBIT ASSEMBLY OF UNMANNED SPACECRAFT

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ABSTRACT

In future, the mission demands on unmanned spacecraft, (whether they be Earth orbiters or deep space probes), will be so great and so complex as to preclude their being small enough to be launched from Earth by chemical rocket. Such spacecraft can be assembled in Earth orbit by suited astronauts, using pre-fabricated modules specifically designed for such orbital assembly. These modules could be standardized, so that any number of spacecraft and mission requirements could be accommodated without extensive need for specialized hardware.

INTRODUCTION

Before the end of this century, the mission requirements of unmanned spacecraft described in this paper will result in spacecraft much too large to be launched in the conventional fashion as a single entity. One viable alternative is to design spacecraft that can be assembled in orbit. Modular construction, with standard modules that can be easily handled in zero-G by suited astronauts, are 'snapped' together to make all mechanical, electrical, gas and liquid connections. Few hand tools would be required. Approaches to standardization, impossible to Earth surface launched designs, are implemented to effectively reduce costs. Discrete modules, delivered by the Shuttle, are assembled by astronauts working from an orbiting workshop.

To date, all unmanned spacecraft have had to be launched inside an aerodynamic fairing on board a chemically powered rocket initiated from the surface of the Earth. This fact has constrained the spacecraft system designer to produce a spacecraft design within very tight weight budgets, capable of withstanding the high dynamic forces induced by the launch vehicle, and to be extremely limited as to the size of various extremities. These extremities, (which are generally solar arrays, antennas, booms for science instrument isolation, etc.), often require an unfolding deployment after the fairing has been jettisoned. Such deployment affects mission reliability, (because of the complexity of the deployment mechanisms required), compounds the weight, power and thermal problems, and could affect spacecraft stability, which must be taken in to account during mission sequencing planning. Assembly in orbit allows the construction of such extremities to assume any size required to meet mission objectives, and they can be assembled in place.

Although some new constraints are placed on the spacecraft system designer in designing a space-

craft for assembly in orbit, these problems are overshadowed by the elimination of many of the most difficult constraints encountered in designs for surface launch. In addition, this new approach affords the opportunity of expanding the state-of-the-art of assembly in orbit by suited astronauts toward the day when it will be an absolute necessity for manned expeditions beyond the Moon. Such expeditions will require such large amounts of survival logistics as to make them impossible, (or at least impractical), for launch from the Earth's surface. Further, assembly in orbit adds impetus to the *raison d'etre* for the presently planned Shuttle, Space Tug, and future manned orbiting workshop/laboratory programmes.

ADVANTAGES AND CAPABILITIES OF ORBIT ASSEMBLY

Advent of the Space Shuttle has generated many ideas which represent it as a platform from which to repair and maintain surfaced launched spacecraft; or as a vehicle for delivering whole spacecraft to Earth orbit, previously assembled and tested on the surface. The concept of assembling large sections of a spacecraft in orbit has also been discussed. But detailed assembly in orbit of 'standard' modules, small enough to be handled by a single astronaut, is an approach worthy of further elaboration. The advantages of such an approach are:

- a) Allows the spaceframe and its associated appendages to be as large as necessary to accomplish a given mission by merely assembling the required modules to each other until the entire sub-assembly/spacecraft has been built up;
- b) Allows each module to be checked after installation before proceeding with further assembly;
- c) Allows replacement/repair of any module if, for any reason it becomes damaged, and-
- d) Allows delivery by the Shuttle of relatively small component modules, isolated from Shuttle launch environment in a way precluded by a completely (or partly) built-up spacecraft.

The system design of the Assembled-In-Orbit (AIO) spacecraft can be specifically executed to assure maximum safety to the astronauts during and after assembly.

From the outset, the assumption is made that the assembly of unmanned spacecraft in Earth orbit can

be accomplished within the present state-of-the-art in every regime of technology, and that no technological 'break-throughs' are required. References made to gas and liquid quick-connect/disconnects, electrical snap-ins and mechanical attachments that occur later in this paper are already within the present state-of-the-art. Skylab astronauts have successfully performed unscheduled extra-vehicular repairs on their damaged spacecraft and conducted manufacturing experiments in zero-G. Their results show that the concept is entirely feasible. In an interview with the press, Mr. Jack Waite, Chief of Skylab experiments, is quoted as having said, "We have learned there is no problem in welding in zero G. Brazing or joining of tubing was accomplished even better in weightlessness than it was done on Earth. If we want to build large structures in space, we foresee no problem".²

SYSTEM DESIGN OF THE AIO SPACECRAFT

A basic philosophy incorporated in the AIO spacecraft system design is that there are no design compromises beyond those that are absolutely necessary for suited astronauts to assemble the spacecraft in orbital environment. That is, it is possible for suited astronauts to assemble the spacecraft, but it is not made especially easy for them. This approach accomplishes two things, namely: (1) prevents overcompromising the spacecraft system design to efficiently execute its mission, and (2) aids in promoting the state-of-the-art of manned orbital assembly. The few exceptions to this philosophy, as contained herein, pertain solely to the physical safety of the astronauts.

Of course, the above philosophy implies that sufficient time must be allowed for assembly, (possibly as much as a year), ahead of the actual launch period required for a particular mission. The overall system design takes advantage of the lack of any constraint, (relatively speaking), on size and weight of the finished product. Thus, the spacecraft may be as large and as heavy as necessary to perform its selected mission. Items requiring huge areas, (such as planar or parabolic antennas, solar cell power arrays, thermal radiators, etc.), would be constructed *in situ* of a number of 'building block' modules. These would be designed to attach sequentially until the structure was complete. The entire design consists of such modules, of a size that can be easily handled and conveyed to the assembly site by a single astronaut. Because weight is no longer a limiting factor, spacecraft masses of 100,000 to a million pounds can be envisaged before the end of the century.

One of the problems that comes to mind with a 'plug in' design is that of controlling and measuring any required critical alignments. Therefore, the design eliminates the need for critical alignments wherever possible. (Some such schemes are presented later in this paper). Where a critical alignment is necessary, it is solved using weight and/or power such that after assembly, the component can be 'homed' to the proper alignment in a servomechanism fashion, and 'locked' in place.

Electrical and electronic subsystems are composed of extremely reliable component parts and radiation shielded. Self diagnosing circuitry and sufficient redundancy are built in to assure operation over the years, (even decades), that might be required for the mission. Weight is used to assure that all circuitry receives adequate thermal environment, and allows for low resistance and redundant interconnections. Electric/electronic assembly modules are checked out individually after assembly to the spacecraft, so that any malfunction due to assembly can be located and corrected prior to proceeding further.

Spacecraft propulsion required for trajectory injection, midcourse correction, orbit adjustment, etc. can be integrated with the reaction control subsystem. Its design incorporates extreme maneuvered safety factors and it, too, is modularized for safety and ease in assembly. Fuel storage is so modularized that any amount of fuel can be accommodated merely by plugging in additional storage tanks to a command manifold until the required amount of fuel is loaded.

The foregoing paragraphs illustrate a few of the many advantages and the added capability resulting from the assembly of an unmanned spacecraft in Earth orbit. The following describes in greater detail each of the technical regimes of the AIO spacecraft.

STRUCTURAL DESIGN OF THE AIO SPACECRAFT

With the Assembled-In-Orbit (AIO) approach, it is no longer necessary to provide a 'structure' around which the rest of the spacecraft is built. The 'structure' of the AIO spacecraft is actually the structural integrity provided by the composite physical characteristics of the various assemblies and modules used in the spacecraft. Only limited assembly hardware is required, in that each module or assembly attaches to the next with snap-on mechanical attachments. These are self-homing and provide positive closing, but with a design feature that will allow dis-engagement, if necessary. This allows for the removal and maintenance of any module damaged by the assembly process. Whole assemblies can be disengaged to allow access to an internal module requiring attention. These larger assemblies can be firmly tied to the workshop in a manner similar to that used to tie down the entire AIO spacecraft to the workshop. This obviates disassembly of previously assembled modules to gain access to the one requiring attention.

The assembly process in orbit is eased and the necessity for hand tools is minimized by eliminating mounting hardware. Those that are required would be battery powered and counter balanced to prevent rotary torque from disturbing the astronaut's zero G attitude.

The basic system design of the AIO spacecraft controls the center-of-mass and moments-of-inertia, to the extent required by the attitude control and reaction control subsystems.

Science instruments, or other devices requiring remote locations on booms to be free of disturbance from the main body of the spacecraft or to meet unrestricted view angle requirements, could easily be mounted on booms of any length by adding on boom sections until the proper length is achieved. Another approach might be to use deployable bi-stems, which are erected with a rotary power tool operated by an astronaut.

Mechanisms, as used on previous unmanned spacecraft, are minimized on the AIO spacecraft. This is due mainly to the lack of a requirement to deploy arrays, booms, etc. However, as space assembly may dictate that items requiring very accurate alignment be equipped with an alignment mechanism, controlled by an externally powered source, such mechanisms will have to be included as part of the spacecraft's design. These would be used to properly align sensors, antennas, science instruments, etc.

PROPULSION AND REACTION CONTROL OF THE AIO

All versions of the AIO spacecraft, whether for near Earth or extra-Solar probe applications, will require some form of propulsive force for orbit insertion/trim, station-keeping, trajectory correction or injection into a trajectory. A single propulsion design should be able to handle all propulsive requirements, be easily adaptable to assembly in orbit, provide maximum safety to the astronauts, and have sufficient flexibility to be applicable to all possible AIO missions.

The following systems were considered:

a) Solid Propellants - Although solids have the attraction of simple installation, they cannot be easily designed for many re-lights and cut-off on command. Grain temperature is a sensitive parameter and thermal control for solids is more complicated than for other systems. Thus, they do not lend themselves to long term space environment storage. Also solids, by their very nature, are not as safe for assembly by astronauts as liquid systems can be made to be. Hence, solids are considered to be a poor choice for this application.

b) Electric Propulsion - Ion engines have come a long way and will undoubtedly have come even further by the time the AIO spacecraft has become a reality. However, the primary propulsion system for the AIO spacecraft will require more 'muscle' than can be provided by electric propulsion. (Note: a large bank of ion engines might be used for extra-Solar applications to reduce time-of-flight to very distant targets. Powered by RTGs, they could be used for acceleration to very high velocities during the 'quiescent' portion of the mission. They could then be used to decelerate to a usable velocity near the target, thus reducing the overall flight time by many months or even years).

c) Bipropellant Liquid - Although very attractive from a performance standpoint, bipropellants require double the gas/liquid connections and tankage, thus complicating assembly, safety and check-out in orbit.

d) Monopropellants - The greatest disadvantage of monopropellant systems is their high weight-to-performance ratio. This type is chosen for the AIO primary propulsion system, in that weight is no longer a limiting factor. Also, monopropellant systems are easy to modularize and represent a high degree of safety to the astronauts. The monopropellant approach fortunately presents other attractive design features of particular interest to the AIO.

The monopropellant system uses the hydrazine/catalyst method of developing its thrust. The maximum thrust level of the engine is chosen sufficiently small to keep the G-forces down to a very small value, in that the completed AIO spacecraft will be quite large and somewhat ungainly and not designed for accelerations much greater than 0.05 to 0.1 Gs. Thus, a catalyst must be chosen which is capable of long and continuous burns, perhaps for several hours, or even days. Easily modularized, the system breaks down into: (1) the modularized pressure tanking and pressure line manifolds, (2) the modularized fuel tanking and fuel line manifolds, and (3) the monopropellant engine module. Active pressurization of the fuel system, (vs. a 'blow down' pressurization system), has been chosen for uniform performance over the long time period that some missions may require. A continuous source of pressurization gas is derived from a 'warm gas' generator, which is also used as a source of pressurant for the reaction control system. The 'warm gas' is generated by passing hydrazine over a catalyst bed, and then stored in an accumulator until needed. The warm gas may have to be passed through a thermal radiator before it is stored in the accumulator. Pressure switches can be used to turn the generator on and off as the pressure is depleted and replenished. The reaction control jets are also of a monopropellant design, sized sufficiently to give adequate attitude control to the size of spacecraft for the particular mission. Thus, several different 'standard' sized jets could be adapted for any particular system design of the AIO.

All gas and liquid lines are connected by a simplified, but positive 'quick disconnect/connect' devices. The fuel tanks, which have been filled, but not pressurized before leaving the Earth's surface, are designed to be safely handled by suited astronauts; it is this requirement which dictates the size/mass of the individual tanks and, therefore, the number of tanks that will be required for any particular mission.

Assembly begins with the installation of a single module incorporating the gas pressure accumulators, gas manifold lines, outlet plumbing to fuel pressurization lines, and all necessary electrical connections.

Next, the fuel assembly is installed. This assembly contains all the necessary 'quick connects' for the pressurization lines, the fuel tanks and the engine, itself. This assembly snaps onto and hooks up the connects from the gas pressurization manifold assembly previously installed. At this juncture, the required number of fuel tanks are installed by snapping them into their 'quick connect' fittings in the fuel/gas manifold assembly, which

also contains their mechanical attachments. The final step in assembly of the primary propulsion system is accomplished by installing the monopropellant engine module in a manner similar to that used for the tanks. The engine module also contains its own method of furnishing thrust vector control, (TVC). Swivelling mechanisms could be used for TVC, but such devices are quite complex and probably less reliable than carbide jet vanes. These are normally installed in the throat of the engine and controlled by the attitude control system during engine burn to maintain guidance of the spacecraft during engine burn. Electrical connections for the TVC vanes would also be made at the time of engine module installation.

The final step is that of installing the reaction control engines. Because these engines can be put nearly anywhere on the spacecraft, their installation may require the use of a simplified tubing module that could easily snap on to other spacecraft modules. Then, by adding these tubing modules in serial fashion, the gas and/or liquid lines could be routed out to wherever the reaction control jet was mounted. Expenditure of hydrazine fuel can be minimized by allowing the spacecraft to drift freely (in some missions) when not required to maintain attitude for antenna pointing, course correction manoeuvres, solar array orientation, or other stable attitude requirements.

ATTITUDE AND GUIDANCE CONTROL OF AIO

The attitude control system of the AIO spacecraft contains all the necessary optical and inertial sensors required to control the reaction engines when maintaining or redirecting the attitude of the spacecraft. The sensor modules can be highly standardized and packaged such as to allow their inclusion or elimination, as any particular mission may require. The inertial sensor module contains an integrating accelerometer, which is used during any primary propulsive thrusting. To obtain the proper ΔV from the thrusting, an appropriate thrust 'count' is transmitted to the spacecraft and stored in a ΔV register. When thrust is developed, the counting accelerometer measures and integrates the effective thrust and 'counts down' the number loaded into the ΔV register. When the correct number of effective 'G counts' has been reached, the register shuts off the engine. This method makes the required ΔV independent of actual mass of the spacecraft, or actual thrust level of the engine and its thrust vector alignment. Thus, some of the critical alignment requirements of the spacecraft have been factored out of the design. Thrust Vector Control (TVC) during engine burn consists of lateral axis rate gyros driving, in closed loop, the jet vanes located in the engine plume.

ELECTRIC/ELECTRONIC DESIGN OF THE AIO

The electronics system contains all the required AIO spacecraft circuitry for all signals below the frequencies used in the RF system. This includes all power processing and distribution, telemetry encoding and command decoding, signal processing, optical and inertial sensor signal routing, scientific

data assimilation and auto-diagnostic test circuitry. The electronic modules can be standardized to a very high degree. Each plug-in module contains adequate radiation shielding, all interconnect wiring, self homing and locking universal interface connectors and any feed-through plumbing that might be required for coolant liquid. Spare electrical circuits are also included for routing data from remotely located sensor modules, science instruments, or other remotely located modules. 'Go/No Go' circuitry terminates at an easily accessible connection on the module. This allows the astronaut to make a quick check after assembly before installing the next module.

One of the most important constituents of the electronics system is a Computer/Sequencer, which is really the 'brains' of the spacecraft. It is capable of receiving any program and storing it for later use. The program may be inserted by the astronauts, or commanded from Earth by RF. The program may be changed at any time and contains many subroutines to control every active system on the spacecraft. For extra-Solar system exploratory probes, a complete program can be stored which will operate the spacecraft for several decades. It can direct spacecraft activities by selecting the most appropriate program to accomplish any, or all parts of a given mission. It monitors all electronic modules, and can switch out a 'sick' module and switch in a substitute, if it determines that selected parameters of that module is not operating within proper limits. (It can also do this for itself, by utilizing a monitoring 'slave' computer which can be switched in as a back up). It can conduct power management routines, integrate optical sensor data and compute navigational errors, or even perform midcourse corrections, to maintain the proper course. Such a capability is particularly suitable for ultra deep space probes that travel out of convenient time range of Earth command.

A special module, the 'heart' of the spacecraft, is used on the AIO to exchange major interconnects. It contains connections for the first electronic module to be installed, an umbilical connection for the final check out and for any special relay test equipment for use in testing the spacecraft remotely from Earth. Mechanical attachments are fitted to this module for tethering the spacecraft to the workshop during assembly. Propulsion modules also attach to this module.

No external wiring bundles or harnesses are used on the AIO spacecraft. All wiring is contained in the separate modules. Interconnecting hardware, integral to the mounting face of each module, are used to incrementally 'wire up' the spacecraft. These connectors are self homing and aligning. After the guide pins of each module are lined up and the module pressed home, a convenient lever on the exposed edge is used to seat all electrical connections, 'quick connect' used to transport gases, liquids, etc. through that module, and any coax or waveguide connectors.

ELECTRIC POWER DESIGN OF THE AIO SPACECRAFT

For near-Earth missions, and exploratory probes and

and laboratories ranging to Jupiter, solar energy conversion to electrical power can be provided by erecting the necessary area of solar cells needed to power any given mission. The AIO approach is appropriate for assembling a Solar Power Satellite³. In this application, a spacecraft assembled in orbit is positioned at geosynchronous altitude by its propulsive system, and using large areas of solar cells, (possibly several hectares), converts this power to microwave energy. This RF power is then beamed to Earth via a large parabolic antenna, (for a very narrow beam and sharp pointing), where it is reconverted to electrical power for domestic distribution. The large areas of solar cell arrays are erected from handlable plug in modules, as is the large parabolic antenna. This subject has been thoroughly researched in the reference and will not be repeated here.

For missions beyond the range of Jupiter, (and particularly out of the Solar system), Radioisotope Thermoelectric Generators (RTGs) are especially adaptable. These devices convert heat from an atomic source to usable electric energy, and also provide heat for keeping various parts of the spacecraft sufficiently warm to survive the cold rigours of deep space. RTGs can be made small enough to be easily handled by a single astronaut for installation. The danger of radiation hazard can be eliminated with adequate shielding. RTGs can be 'added on', until their total output exceeds that of the maximum spacecraft power demand.

For unmanned spacecraft applications, fuel cells do not seem to lend any particular advantage over those power sources previously discussed. Batteries are used on solar powered spacecraft to maintain power continuity at any time the solar array is not Sun oriented.

THERMAL CONTROL OF THE AIO SPACECRAFT

No matter what mission is chosen, the thermal design of the AIO spacecraft would be totally independent of solar radiation. That is, all solar thermal energy is rejected and spacecraft thermal control is maintained by sunbanding or radiating to deep space the thermal energy generated within the spacecraft. Thermal protection of the AIO may be difficult during the assembly period. Temporary blankets can be provided, (a 1/2 Skylab), or workshop power can be used to heat local 'cold spots', until the assembly is complete. The spacecraft can then be powered up to supply its own thermal control. Thermal blankets which fly with the spacecraft are the last items to be installed. For RTG powered missions, heat pipes and/or active fluid lines deliver heat from the RTGs to the balance of the spacecraft. Excess heat is dumped by active or passive radiators, as required. Each plug-in module has, to the greatest degree possible, its own thermal control protection. Tubes carrying active thermal control fluids are connected with a quick disconnect similar to those used for the propulsion liquid/gas lines, and snap in when the module is assembled to the spacecraft.

RF RECEPTION AND TRANSMISSION DESIGN OF THE AIO

Relatively unlimited size and weight advantages offer RF design capabilities that cannot be attempted in surface launched designs. However, very high power transmitters may require an excessive amount of raw electrical energy, or low power transmitters could require very high gain (large parabolic) antennas. The latter would require a high degree of attitude control pointing accuracy, because of very narrow beamwidths. Thus, it would be a system design goal of the AIO spacecraft to determine the optimum trade-off between the power of the transmitter and the aperture (size) of the antenna. One exercise conducted involved the use of a 100 meter diameter parabolic antenna operating with an RF transmitter of 500 watts at S-band, (2 GHz). The 100 meter diameter antenna has a beamwidth of 0.01° and requires the attitude control system to maintain attitude stabilization to that same accuracy. For short periods of time, (limited to avoid unnecessary burning of reaction control fuel), this figure did not seem to be beyond the present state-of-the-art. Assuming a ground receiving antenna with a figure-of-merit of at least 40 dB, (such as the 64 meter diameter antenna used at Goldstone, Calif.) the system would allow reception of better than 5 kilobits per second at the range of Pluto! Thus, high resolution TV pictures of Pluto's surface would be possible. At four times the range of Pluto from the Sun, (13 billion miles), a data rate of 1.5 kilobits per second could be realized. However, these ranges strain today's capability to acquire and lock onto the received signal.

Another AIO spacecraft requiring a high gain antenna with a narrow beamwidth is the Solar Power Station. For this application, a relatively small target on the surface of the Earth must be accurately aligned with the satellite's transmitting antenna to obtain the highest efficiency of received energy and to avoid splashing high energy microwave about the countryside. This could be a serious safety problem, for microwave is injurious to human, plant and animal life.

The large parabolic antenna, (or planar array for some applications), is assembled from snap-together modular pieces, 'building block' fashion. Another approach uses an inflatable design which employs aluminumized plastic sheet inflated with a settable foam. This approach eliminates detrimental Solar effects, (such as parabolic focus heating and Solar Wind disturbance), by delaying the inflation until the spacecraft is at sufficient range to make such disturbance negligible. Such structures are light enough to be individually guided, if necessary.

Transmitters with output powers much greater than 500 watts can be provided rather easily. Transmitters of 1,000 to 10,000 watts are possible, with liquid cooled Travelling Wave Tube Amplifiers, (TWTAs). These transmitters may operate in short 'bursts' to relay recorded data, or for real-time television transmission. Rechargeable batteries support these short term transmission periods.

Smaller parabolic and 'omni' antennas are required in some applications for receiving commands during early midcourse corrections and out to ranges where

the delay time between Earth and the spacecraft make such control impractical.

TEST REQUIREMENTS FOR THE AIO SPACECRAFT

By assembling the spacecraft in orbit, we eliminate the expensive and time-consuming requirement for system dynamic testing to simulate launch from the surface by chemical rocket. Individual modules must nevertheless be delivered from the surface via the Shuttle to the assembly point in orbit. But here, it is quite easy to pack each module for launch so that it is isolated from any extreme dynamic environment. However, each module sees some level of dynamic environment from both the Shuttle launch and from spacecraft propulsion activities. Thus, each module design is subjected to qualification testing at those expected levels. The advantages of standardization reduces this type of testing to a non-recurring requirement.

The system design of the AIO spacecraft, for each configuration, must be so executed that the entire spacecraft can be assembled and functionally tested on the surface of the Earth. Every plug in module must be shown to fit properly and be easily assembled before it is taken to space for its assembly in orbit. Thermal/vacuum testing is not conducted at the system level, but individual modules are subjected to a thermal-vacuum test. All gas and liquid connections are leak-tested. The monopropellant and reaction control jets are then operated as a complete system. Items that cannot be assembled in a 1G environment are kept to a minimum. For these, other tests must be devised to assure that they will work to specification when assembled in orbit.

The astronauts who will assemble the spacecraft in orbit will witness all assembly and testing of the spacecraft on Earth. Their previous training might include assembly of mock-ups while wearing space suits, and underwater zero-G simulation of the various assembly tasks they will face in orbit.

AIO INTEGRATES MANNED/UNMANNED TECHNOLOGIES

The experience already gained in space can certainly be brought to bear on the AIO spacecraft. Past unmanned programs are precursors for the unmanned spacecraft systems destined for larger, and more ambitious programs of the universe. The past manned programs have laid the groundwork for man working in space, the only 'factory' large enough to assemble unmanned spacecraft of great size and mass. Together, the two technologies can be teamed to carry man's exploration of the universe into another historical era.

THE BONDING ORBITING WORKSHOP

The design of future manned orbiting workshops must certainly consider the requirements of assembling spacecraft in orbit. The workshop attitude/reaction control systems must be designed to allow for the additional mass of unmanned spacecraft, as assembly proceeds, while still firmly tethered to the workshop. The workshop power system must be designed

to supply the power required to check operation of the unmanned spacecraft, as well as battery recharging facility for hand powered tools. The workshop should also provide an area for some simple repair jobs, to allow repair of any item damaged during the assembly process. (Of course, it is expected that any major damage would require that the item be returned to Earth for the major repair work required which could not be accomplished on the workshop).

A tape library is provided for the various taped instructions, (described later), which might be required for the various levels of assembly. This also includes means for recording new tapes, possibly from Earth based control via RF link.

Emergency retrieval for any astronaut having life support problems while working on the unmanned AIO spacecraft must be provided. This includes a means for retrieving spacecraft parts that might accidentally drift away from the reach of an astronaut during assembly. Thermal blankets or active thermal control methods for the partially assembled spacecraft are employed.

THE SHUTTLE DELIVERY SYSTEM

It is not envisioned that any specific design requirements are to be placed on the Shuttle for the delivery of AIO spacecraft parts and assemblies to the workshop. All of the various assemblies needed are packaged in standard plastic foam containers, which are returned to Earth by the Shuttle for subsequent use. It is a design goal to not have any packing materials which, by their nature, are expendable. But if required for some special application, the material is returned on the empty Shuttle for disposition on the surface. No packing material or refuse of any kind is left floating in space or taking up room inside the workshop. Indeed, the sequence of assembly is designed such as to not require that any assembly be taken into the workshop. No additional assembly work in the workshop can be envisioned which could not have been done on Earth prior to delivery. Unless some assembly needs light repair, all items are removed from the Shuttle cargo bay and immediately assembled to the unmanned spacecraft. If the shuttle mission precludes this, (i.e., if the Shuttle must de-orbit and return to Earth before the parts can be assembled to the AIO), then some provision is made in the workshop for a 'bonded stores' area.

The Martin-Marietta M-509 'flying arm chair' unit⁴ having been tested on the Skylab program, would be of great value in transporting assemblies and modules from the Shuttle cargo bay to the assembly area and for general transport of the astronauts. Adapted for assembly use, the 'arm chair' would contain pockets for tools, a strap-on rack for carrying the modules to be assembled, additional life support expendables, temporary thermal shields, etc. In any case, assembly astronauts are going to require some method of 'valving' their way around.

HUMAN FACTORS CONSIDERATIONS

In considering the maximum mass that a single astro-

naut could handle in zero-G, it is assumed that he should be able to handle the equivalent of his own mass, which when suited, can be as much as 250 to 300 pounds. (This assumption is based on the case of a stricken astronaut being 'towed' to a place of safety by his partner). But to be on the safe side and still stay within practical limits, the spacecraft modules are kept to something like 50 to 75 pounds apiece. Should any one assembly module require a single unit mass of greater than this, then two astronauts working as a team should be able to handle it in orbital environment. Although the modules appear 'weightless' in orbit, they still have mass. Care must be taken to slow the modules down, (with the flying arm chair propulsion or other means) as it arrives at its assembly point to prevent collisions with the partly assembled spacecraft.

The astronauts are tethered to the workshop at all times. Assembly modules are tethered to the astronaut, (or to the flying arm chair, to which the astronaut is safely belted) until it is firmly attached to the spacecraft. The tether is then removed from the module.

work periods depend on the particular astronaut. Mission planners know the length of time required to fully assemble and check out the completed spacecraft to meet the critical launch periods. Skylab missions have shown that astronauts were ahead of their work schedules and asking for more chores to keep them active. For Earth orbit assembly reasons, the assembly supplies will depend on the cargo of a particular Shuttle mission and the stage of development of the AIO assembly at any point in time. It seems reasonable that as long as there are modules in the cargo hold of the Shuttle to be installed, each astronaut should be able to work at least a 3 hour shift, with an hour or 2 off inside the workshop before beginning his next shift. With experience and acclimatization, these times could be adjusted accordingly.

assembly astronauts should be 'rotated' to Earth at regular intervals, which is suggested to be at least every 8 weeks. Regular medical check ups are performed and must be passed 100%, or the astronaut is 'grounded' and replaced. While on Earth, the astronaut is briefed on the next phase of assembly and reports any difficulties encountered in the previous phase of assembly.

During assembly, each astronaut would carry a cassette tape playback device, which feeds directly into his suit communications equipment. He can play forward, stop, reverse and replay, but he cannot record or erase. Before leaving the workshop, the astronaut listens to this cassette recording of the next procedure and clarifies any misunderstanding he might have. After assembly, the tape is returned to the library and saved for the possible eventualities of disassembly and reassembly of that particular module. One of the astronauts will be required to play the role of quality control inspector, as a second set of eyes to any assembly procedure. This assures that at least two astronauts confirm the procedure is correct and prevents mistakes and poor quality work due to 'space rapture', space sickness, fatigue, etc.

MODULAR DESIGN FOR MANNED ORBITAL ASSEMBLY

With the personal safety of the astronauts always in mind, the critical portions of the design are broken down into convenient 50 to 75 lb. chunks. These can be handled and assembled relatively easily. One problem is the fuel tankage for the mono-propellant engines. These are designed as individual tanks, man-rated and shaped something like the familiar shop acetylene tanks (long cylinders). They contain the pressurization bladder and are fully fueled, but not pressurized. They are fitted with the necessary quick connect/disconnects. A lever arrangement allows the astronaut to evenly engage enough force to seat the quick connect. The lever is part of the tank receiver/manifold and would become part of the tank hold down strap after installation.

Large areas, such as the solar panels and antennas are built up of convenient 'building blocks' which snap together. For their own protection during the Shuttle flight, sections of the solar array are folded such that only their back sides are exposed. With only two sections per assembly, they are protected from damage of the active cell area until they arrive at the assembly area. Here, it is quite easy to unfold them and snap them into place. The cell side has a margin around the edge of every panel 3 to 4 inches wide for 'finger grip' handling.

All electric and electronic modules are sized consistent with the 50 pound rule. They have short steel dowels which match holes in the adjacent face of the mating module. Mating faces contain all electrical, liquid, or gas connections. Once aligned by the dowels, a lever is thrown 'over center', which seats all connections. Where practical, light emitting diodes (LEDs), light detecting diodes (LDDs) fibre optics, etc. are used to transmit low level signals across mechanical interfaces. After assembly, the astronaut conducts a 'go/no-go' test, designed to assure the module is properly installed, before proceeding with the assembly of the next module.

An 'unsafe' module is the ATG, which must be designed to have adequate shielding to prevent subjecting the astronaut to dangerous radiation levels. It is designed to absolutely assure that the module cannot burst open, even through improper handling. Each ATG module has fittings allowing mechanical and electrical attachment of as many units as required for a particular mission, while preserving the designed neat-flow path and overall spacecraft mass properties.

All thermal control blankets are fitted to the spacecraft as the last assembly task. Each blanket has been pre-fitted and has the feature of 'snapon' fittings for easy, yet adequate, attachment. A method of neat-tight sealing must yet be developed for orbit assembly of the blankets.

POSSIBLE MISSIONS FOR THE AIO SPACECRAFT

Missions chosen for the AIO spacecraft are those which cannot be accomplished with surface launched spacecraft. They are as follows:

MISSIONS TO OTHER STAR/PLANET SYSTEMS

Missions in this category require great banks of RTGs for heat and power, extremely large antenna gains, high RF power transmitters, computers programmed to conduct the entire mission without intervention from Earth, long life components designed for wide temperature ranges, and a comprehensive science experiment complement to make the mission cost effective.

PROBE OR PLANET ORBITER INSIDE THE SOLAR SYSTEM

- 1) Cometary Fly-Bys - These require high propulsive maneuverability with the quantity of fuel necessary to perform the intercept. They also require a large science complement, (possibly including real-time television) and the necessary RF and electric power to support the mission.
- 2) Planetary Orbiter Automated Laboratory - This is a completely automated orbiting laboratory for the investigation of the planet surface and natural planetary satellites. They are particularly adaptable to Jupiter, Saturn and the other outer planets. They require RTGs for heat and power, a large science complement, the necessary RF power and antenna gains for high data rates (including television), and re-programmable sequencer/computer capability. They also carry hard or soft-lander probes for investigation of the planet's atmosphere and surface. This would require probe data pick up and relay RF equipment.

GEOSYNCHRONOUS SATELLITES

1) Domestic Communications - At the time of this writing, 'parking spaces' at geosynchronous altitudes are already becoming hard to get. In future, it may become necessary to allot one parking space per nation, or group of nations (in congested areas) for a domestic applications satellite. Thus, using the ALU concept, a single satellite can be constructed and transferred to synchronous orbit altitude under its own power. This satellite can have enormous solar arrays, an array of all the necessary antennas, a number of high power RF transmitters with all the necessary electronics and adequate propulsion and fuel to maintain its parking station. With regular maintenance by the Space Tug, a properly designed communications satellite can adequately serve the sponsoring nation(s) for 50 to 60 years.

2) Solar Power Relay³ - With fossil fuels and other energy sources rapidly dwindling, it may be necessary to convert solar power from geo-synchronous orbit and relay it to earth as convertible microwave energy for use as domestic power. This satellite can be constructed in orbit and transferred to geo-synchronous orbit by its own propulsive power. It includes a gigantic solar array area and high RF power microwave transmitters, a very accurate attitude control system for pointing narrow beam parabolic antennas at a very small target, an alarm system to shut down the microwave transmitters if the attitude control fails (to prevent microwave damage to life on earth) and sufficient fuel for the atti-

tude/reaction control systems to track the Sun through 360° every day. With regular service via the Space Tug, this satellite could provide power for several decades.

3) Outer Space Communications Relay - In geo-synchronous orbit, a large communications relay station can be used to track space probes to distant star systems and laboratories orbiting the outer and inner planets. Employing extremely large, steerable antennas, highly sensitive receivers (in a noise-free environment), RF transmitters for relay to Earth or other communications satellites, adequate solar arrays for the necessary power, a very sensitive attitude maintenance system (with necessary reaction control fuel) and a long range command relay link, this satellite can perform deep space mission tasks that cannot be performed from the surface of the Earth.

4) Large Astronomical Observatory⁵ - Already, astronomers are complaining that orbiting satellites are interfering with their view of the universe. As more and more satellites, of ever increasing size, are put into Earth orbit, the situation can only become worse. The solution, of course, is to construct a Large Space Telescope in orbit; transfer it to geo-synchronous orbit by its own propulsive system, and view the stars and galaxies of the universe from an unobstructed vantage point. Very large reflecting mirrors with extreme light gathering power can be constructed in zero-G. Forming and silvering are easier to accomplish in high vacuum and zero-G than they are on Earth. The satellite has adequate solar array area to supply power for high resolution real-time television transmission to Earth 24 hours a day. High data rates could be used to perform spectrum analyses and obtain other scientific data from the targets. The observatory includes a wide-band radio astronomy antenna. It could also be used for 24 hour observation of Solar astronomical phenomena.

MANNED EXPLORATORY SPACECRAFT

Although this paper has been dedicated to the concept of assembling unmanned spacecraft in Earth orbit, the technique is equally applicable to manned spacecraft. The methods perfected in assembling unmanned spacecraft will undoubtedly pave the way for the orbit assembly of manned spacecraft in the very near future.

Simple calculations show that the extreme logistics demands of an exploratory manned mission to even the nearest of planets, (Mars and Venus), requires great quantities of life support expendables for even a very few men. The food, water and air required for just 3 men for as little as a year could preclude the mission from being launched from the surface of the Earth. Therefore, assembling the spacecraft, stocking it with provisions, preparing it for flight and injecting it into a particular trajectory can all be accomplished rather easily from Earth orbit.

REFERENCES

- 1) A. U. Tischler, *Low Cost Space*, *Astronautics and Aeronautics*, Volume 11, No. 5, May 1973, pp. 22-23.
- 2) Associated Press Release (U.S.), date-lined September 11, 1973.
- 3) Peter L. Glaser, *Solar Power via Satellite*, *Astronautics and Aeronautics*, Volume 11, No. 8, August 1973, pp. 60 to 68.
- 4) *Aviation Week & Space Technology*, Volume 99, No. 8, August 20, 1973, p. 23.
- 5) C. K. J'Well, *Optical Space Astronomy and Goals of the Large Space Telescope*, *Astronautics and Aeronautics*, Volume 11, No. 4, April 1973, pp. 22 to 27.