AUTOMATED RESUPPLY OF CONSUMABLES: ENHANCEMENT OF SPACE COMMERCIALIZATION OPPORTUNITIES

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ABSTRACT

This paper addresses work performed at Rockwell International's Space Systems Division to investigate the feasibility of, and develop concepts for, automated and/or robotic resupply of consumables on orbit. The work focuses on the resupply of satellites and is described in five sections. First, the various problems relating to resupply on orbit are discussed: for example, economic concerns, fuel handling problems, and safety issues. Next major methods of effecting fuel transfer on orbit are summarized, together with their advantages and disadvantages. Direct fuel exchange is emphasized as the most feasible technique. Third, guidelines are developed for automated/robotic refueling mechanisms to accomplish on-obit consumable resupply. For example, the guidelines cover safety, reliability, maintainability, alignment, induced loads, thermal protection, leaks, extravehicular activity (EVA) interface, and so on. The fourth part of the paper covers the development of design concepts for satellite resupply robotic interfaces that comply with the guidelines. Concepts include servicer fluid transfer system and satellite propulsion system, and a combined docking/umbilical device. Last, future technical development in these areas are discussed.

INTRODUCTION

There are several reasons why on-orbit refueling is a necessary capability. Fuel may be consumed faster than expected: fuel may leak unexpectedly. Unless remedied, either situation could bring about a severe financial loss to the owners of the satellite or to its insurers. In addition, satellites may be built to require refueling after a known number of years, for example, the Gamma Ray Observatory (GRO) is expected to need refueling about 3 years after launch. Most of the proposed Space Exploration Initiative (SEI) assets require on-orbit fueling. Furthermore, if on-orbit fueling capability was available, many more satellites would be designed accordingly to extend their life and reduce usage cost. However, since development of this capability requires substantial funding, it is not feasible to absorb all its cost in one satellite program/project, unless it is specifically designed to address this issue. So far NASA, DoD, and commercial satellite builders have avoided incorporating on-orbit refueling into their requirements on a broad scale. However, we believe it will not be long before the designers of future satellites will incorporate on-orbit refueling, wherever it is economically feasible, to take advantage of its economic and safety benefits.

There are two main methods for accomplishing on-orbit refueling: EVA crew or a remotely operated robotic/automated device that does not need nearby human presence and control. We believe that automated/robotic refueling presents many advantages over EVA methods. The EVA crew may have problems reaching the satellite, even if it is in an EVA compatible orbit. EVA time is an expensive commodity and an EVA refueling excursion would greatly add to a mission's cost. EVA is time limited to about 6 hours. If refueling takes longer, a second EVA team may have to make an EVA excursion. In addition, considerable EVA time is spent in task setup and in translation to the work site. Last, and most important, EVA operations carry a greater risk than intravehicular activity (IVA) operations. The environment is more hazardous, and the propellant, especially hypergolics, impose increased safety risks.

If an automated/robotic system is used to refuel the satellite, a new set of problems must be addressed. Although the human is no longer in close proximity to the refueling operation, safety issues still concern avoiding damage to the satellite by the fueling device and vice versa. Other issues concern the interface between the satellite and the robotic fueling system. For example, markings and color coding must be machine readable, fluid connectors must be compatible with robotic/automated operations and stability/handholds must be compatible with the device's stability system. The compatibility requirements should be embedded as a set of standards or guidelines so that compatibility exists across many classes of satellites that are then serviceable by the same type of automated/robotic device. This paper therefore addresses the problem of providing concepts and guidelines for robotic/satellite interface so that the satellites can be easily refueled by an automated/robotic system.

METHODS OF PROPELLANT TRANSFER

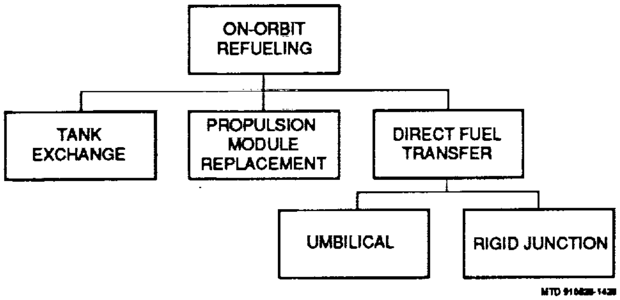
There are three major methods of on-orbit propellant transfer: direct fluid transfer; tank exchange; and propulsion module exchange (Refer to Figure 1).

Direct Fluid Transfer

Direct fluid transfer, as the name implies uses the same concept as a car at a service station: fluid is directly transferred from the servicer tank to the satellite tank.

Tank Exchange

This method involves the replacement of the empty fuel tank by a full fuel tank. The fuel tank is therefore an orbital



"Figure 1 - Metholds of On-Orbit Fuel Transfer."

replacement unit (ORU) and must accommodate all the features that allow it to be safely and efficiently handled by a robotic/automated system. For example, it should have an appropriate grappling point. It should have self-guiding and -locking mechanical, fluid, and electrical connectors.

Propulsion Module Exchange

This method requires replacing the entire propulsion system, which becomes an ORU. This method requires the propulsion system to accommodate all necessary features for remote handling. The method permits the removal of a propulsion system for service at a space maintenance facility. The propulsion module will include fuel tank, thrusters, fluid lines and fuel management system.

Trade Study

A series of trade studies were performed to review the merits of each concept. Direct fueling had the least impact on satellite design. It also allowed full utilization of available fuel. Finally, it required the smallest number of interfaces. The disadvantages include longer operation time and safety concerns related to actual displacement of the fuel from one tank to another. Figure 2 shows the required interfaces for each method.

DIRECT	TANK EXCHANGE	PROPULSION MODULE EXCHANGE
• SERVICER - SATELLITE BERTHING I/F	• SERVICER - SATELLIT BERTHING I/F	• SERVICER - SATELLITE BERTHING I/F
• SERVICER - SATELLITE FLUID I/F	• ORU I/Fs SERVICER SIDE - FLUID - MECHANICAL - ELECTRICAL	• MODULE BERTHING I/F • MODULE INTER-STORAGE I/F
	• ORU I/Fs ON SATELLITE SIDE - FLUID - MECHANICAL - ELECTRICAL	
	• ORU INTERSTORAGE I/F	
	• TETHER I/F	

"Figure 2 - Required Interfaces for Fluid Transfer Metholds."

The tank exchange method reduces operation time and lessens the number of interfaces. On the other hand, there are four disadvantages. First, the tank exchange should always take place before the tank is completely empty. This wastes valuable fuel and reduces the overall cost efficiency. Second, a tank needs to be carried to the rendezvous site for the fueling of each satellite, thus the servicer weight will increase significantly. Third, the capability for exchanging tanks imposes too many design constraints on the satellites. Fourth, transfer of such a large mass from the servicer to the satellite and the resulting sudden shift in the center of the gravity raises some concerns regarding control and system stability.

Propulsion module exchange offers the same advantages and disadvantages as the tank exchange option. However, its disadvantages are more pronounced, which resulted in making this option the least favorite.

Based on the results of the trade study, it was determined that direct fuel exchange is the most cost-effective and feasible technique. Therefore, this paper concentrates on this method.

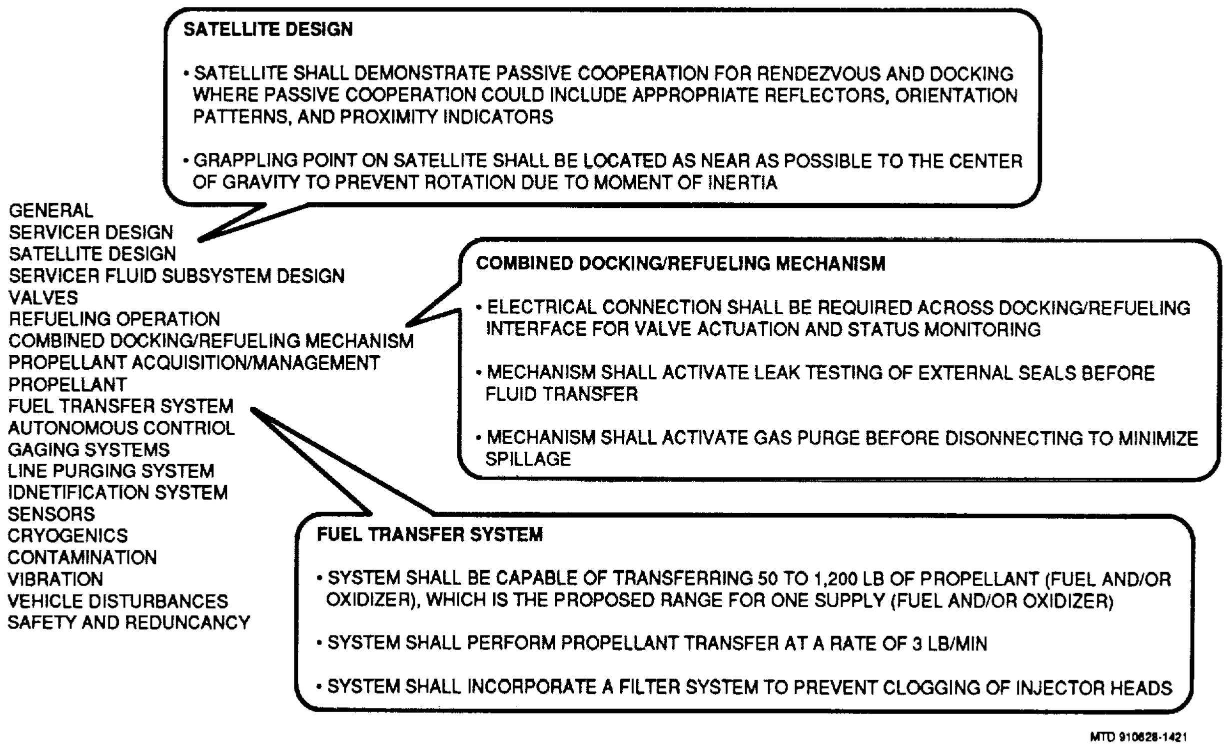
Direct fuel transfer can be accomplished through different methods such as use of an articulated arm to make the connections between fuel lines, electrical connectors and satellite, or a dedicated self guiding umbilical. To identify the best method for making the interface connections, various options were studied. Since the servicer device must dock with the satellite, a feasible approach is the combination of the device for direct fueling and the docking device to form a combined docking and refueling automated umbilical. Unlike an articulated arm that may perform many other tasks, this system is an intelligent mechanical system that only performs one function: docking/mating interface connections. This approach minimizes the interface area/envelop between the servicer and satellites, which reduces the constraint on satellite design. Furthermore, both the docking and mechanism developed for making fluid and electrical connections could utilize the same gross positioning and self-alignment system, which reduces system weight. Both docking and fueling connectors could be driven by the same set of redundant motors. Thus, the chances of misalignment or snagging would be lessened because the interfaces are rigid and follow a predetermined path. Finally, since both docking and making the interface connections are performed in parallel, task operation time is reduced.

AUTOMATED/ROBOTIC REFUELING GUIDELINES

A preliminary set of design guidelines were developed to cover both satellite and servicer subsystems. These guidelines will be used by satellite designers to design the interfaces compatible with the servicer. Guidelines cover the following areas:

- General
- Servicer design
- Satellite design
- Servicer fluid subsystem design
- Refueling operation
- Combined docking and refueling mechanism
- Propellant acquisition/management
- Propellant
- Fuel transfer system
- Autonomous control
- Gaging systems
- Line purging system
- Identification system
- Sensors
- Cryogenics
- Contamination
- Vibration
- Vehicle disturbances
- Safety and redundancy

Figure 3 shows typical examples of these guidelines for depicted areas. Adherence to these guidelines ensures



"Figure 3 - Summary of Guidelines."

compatibility between the satellite and the servicer. The guidelines provide a compatible interface envelop in which one servicer could service different satellites. It is only through such approach that on-orbit refueling could be cost effective.

DESIGN STANDARDS

Design guidelines were used to conceptualize a series of standards (design solution) that could be used in the satellite and servicer design. Where feasible, satellite designers should be encouraged to use standardized designs. This will cut down on development, certification and operation costs. Preliminary design standards where developed for these two areas:

- Servicer fluid transfer system and satellite propulsion system
- Combined docking/refueling automatic umbilical

Servicer Fluid Transfer and Satellite Propulsion System

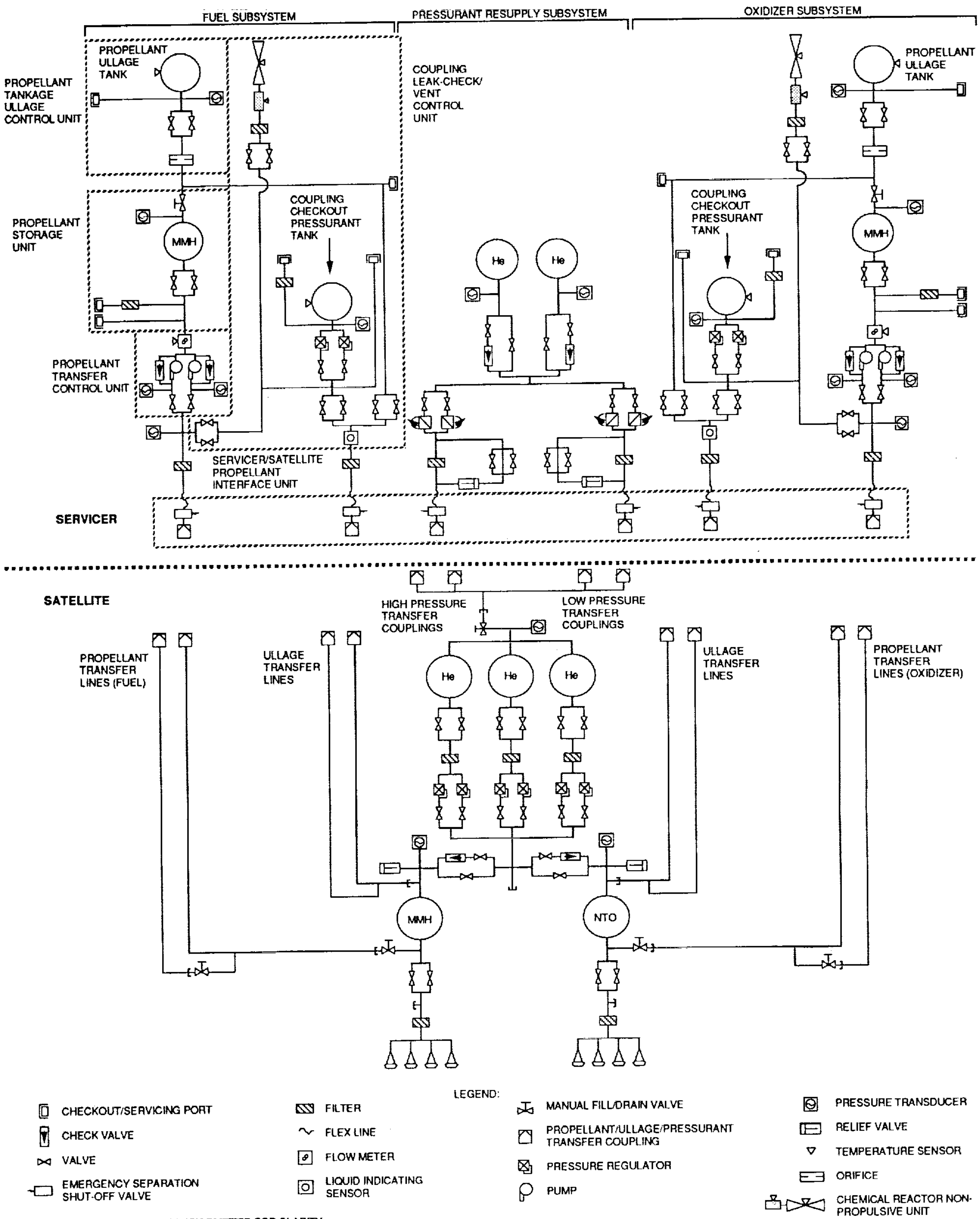
Figure 4 shows the schematic for the servicer fluid/pressurant transfer system and the propulsion system schematic for the satellite. Direct fluid transfer using ullage exchange is recommended as this is a pressure-regulated propulsion system. Here, the degree of redundancy is omitted for clarity. The fuel/oxidizer transfer system, shown in the upper half of the diagram consists of five subsystems:

1. Propellant storage unit
2. Propellant tankage ullage control unit
3. Propellant transfer control unit
4. Coupling leak-check/vent control unit
5. Servicer/satellite propellant interface unit

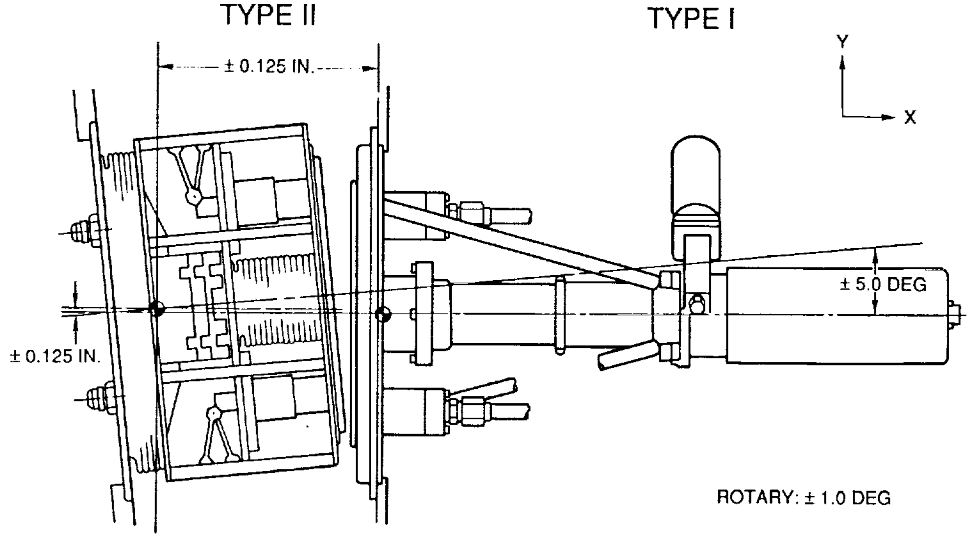
Combined Docking/Refueling Automatic Umbilical

A refueling automatic umbilical should be combined with the docking mechanism for these four reasons: Interfaces are simple; operations are simple since only one mate/demate operation is performed; a set of redundant motors could drive docking and utility connectors; the close proximity of the fluid and electrical connectors to the docking point minimizes mating misalignment. Problems of safety and added complexity preclude the recommendation of a quick-disconnect (QD) mechanism. Should a failure occur during demating, either pyrotechnic or nonpyrotechnic release systems may be used. If connectors/umbilical extend beyond the servicer's thermal blanket, insulation may be needed for thermal control. Multilayer insulation (MLI) or heaters active only during fluid transfer could prevent propellant freezing.

A market survey of available connectors identified the Moog automated umbilical connector (AUC) with its $\pm$5.0 degree misalignment envelop as a potential design (Figure 5) for fluid, data, and power connectors. The misalignment envelop defines the allowable tracking error for a robotic/automatic servicer or a docking system. Since several connectors need to be mated simultaneously, the possibility exists that one of the connectors may stick in the mating process. A possible solution to this problem involves spring assemblies in the design. Each connector would be mounted on an independent spring assembly. When a connector sticks, its axial motion stops and the spring behind it compresses, allowing the remaining connectors to continue to be mated. With redundant connectors, a failure of this nature would not preclude the propellant/pressurant transfer.



"Figure 4 - Fluid Transfer System and Satellite Propulsion System."



"Figure 5 - Moog AUG."

FUTURE TECHNICAL DEVELOPMENT

On-orbit fueling is a desired capability and some satellites such as GRO have already included the necessary interfaces. The desire will grow and will become a necessity as new NASA and DoD programs are launched. SEI is a good example of such programs.

A comprehensive set of design guidelines and design standards should be developed prior to or in parallel with the design of the first class of assets that require on-orbit fueling. Therefore, work performed here should be continued by NASA, DoD, and technical committees to facilitate on-orbit refueling and make it more effective.

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