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THE DESIGN AND DEVELOPMENT OF A MOBILE TRANSPORTER SYSTEM FOR THE SPACE STATION REMOTE MANIPULATOR SYSTEM

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ABSTRACT

This paper describes the analyses, selection process, and conceptual design of potential candidate MobileTransporter (MT) systems to move the Space Station Remote Manipulator System (SSRMS) about the exposed faces of the Space Station truss structure. The actual requirements for a manipulator system on the space station will be discussed, including potential tasks to be performed. The SSRMS operating environment and control methods will be analyzed with potential design solutions highlighted. Three general categories of transporter systems will be identified and analyzed. Several design solutions have emerged that will satisfy these requirements. Their relative merits will be discussed, and unique variations in each system will be rated for functionality.

INTRODUCTION

The National Space Transportation System (NSTS) Shuttle Orbiter makes use of a highly-refined Shuttle Remote Manipulator System (SRMS) to perform various on-orbit manipulative tasks such as deployment and retrieval of orbiter payload bay packages and satellites, space structural assembly, and remote servicing and maintenance. This system was designed to handle payloads no larger than those that could be transported in the orbiter payload bay. The typical mission length was to be on the order of two weeks or less, with potential for complete refurbishment of the SRMS between flights, so the SRMS is presently an orbital replacement unit (ORU) in itself, with no provisions for on-orbit repair.

The NASA Space Station presents an entirely new arena for a manipulator system. The expected station lifetime of up to 30 years, the large potential payloads of up to 120,000 Kg. (the shuttle orbiter), and the limited on-orbit servicing capabilities dictate a new approach to a manipulator system. The harsh environment of long-term exposure to atomic oxygen, severe extremes of heat and cold, and the conditions of a vacuum and zero gravity require elaborate engineering analyses and studies for the development of space-borne manipulator systems. Limited station power resources necessitate energy-efficient systems design. NASA has requested that the National Research Council of Canada, in conjunction with Spar Aerospace Limited of Toronto, Canada, redesign existing manipulator systems to form a Space Station Remote Manipulator System (SSRMS) that will satisfy these new requirements.

One of the present forms of the SSRMS is 17.4 meters in length , and weighs approximately 860 Kg, which is significantly larger than the present shuttle orbiter manipulator system. This SSRMS features a double-ended end effector configuration, and has seven degrees of freedom due to replacing the standard shoulder with a three-axis end effector / wrist assembly. Higher power and data transfer rates (end effector to payload) with potential for thermal and fluid transfer are special requirements to be considered. The re-designed end effector operates as a standard three-wire snare, or as a shoulder mount with side-attachment latches for the required base stiffness. The new mounting configuration of this and other SSRMS designs, and the larger overall size and mass, place special design constraints on potential transporter candidates. These requirements will be discussed as transporter design drivers, and an evolutionary series of transporter concepts will be presented and discussed.

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SPACE STATION MANIPULATOR SYSTEM TRANSPORTER REQUIREMENTS

NASA has outlined a series of basic requirements for a manipulative system on the space station, and the Canadian government and U.S. contractors have responded with variations in designs to bring down the development costs and enhance performance. The following requirements have been defined:

I The Mobile Transporter (MT) and attached Mobile Remote Servicer (MRS), which together comprise the Mobile Servicing Center (MSC), shall be capable of traversing all designated space station truss faces. To accomplish such motion, the mobile transporter shall be capable of- (a) straight traverse along a clear truss face, (b) direction changing within tight quarters, and (c) plane changing (from one face to another) at any clear area on the truss structure.
II The MSC shall have the capability to move and manipulate payloads of >100,000Kg (orbiter).
III The MSC shall have the capability of self-contained operation for periods of up to 6 hours.
IV The MSC shall be able to be controlled from an EVA station on the MSC or from the station.

These are examples of the basic requirements that have been the design drivers throughout the definition stages of the MSC development. Many of these "requirements", such as an on-board battery system for 6 hours of independent operation, are open to discussion as to their actual need for a potential system, but are presented as a departure point for design studies. Some of the responsibilities of the MSC will be berthing/deberthing of the Orbiter, Orbital Maneuvering Vehicles (OMV's), Orbital Transfer Vehicles (OTV's) and other free-flying platforms, removing payloads from the Orbiter, transporting and installing the payloads to the desired truss location and retrieving payloads for Earth return. As the name implies, a major function of the MSC will be maintenance and servicing of the Space Station and associated payloads, as well as transportation of various payloads and experiments.

The Mobile Servicing Center consists of four parts, the Mobile Transporter, the "utility platform" or base structure, the Space Station Remote Manipulator System (SSRMS) and the end effector(s). Figure (1) shows a current baseline design under study. This MSC concept utilizes the Canadian-developed "utility platform" / SSRMS structure in conjunction with a dual-drawbar push pull transporter.

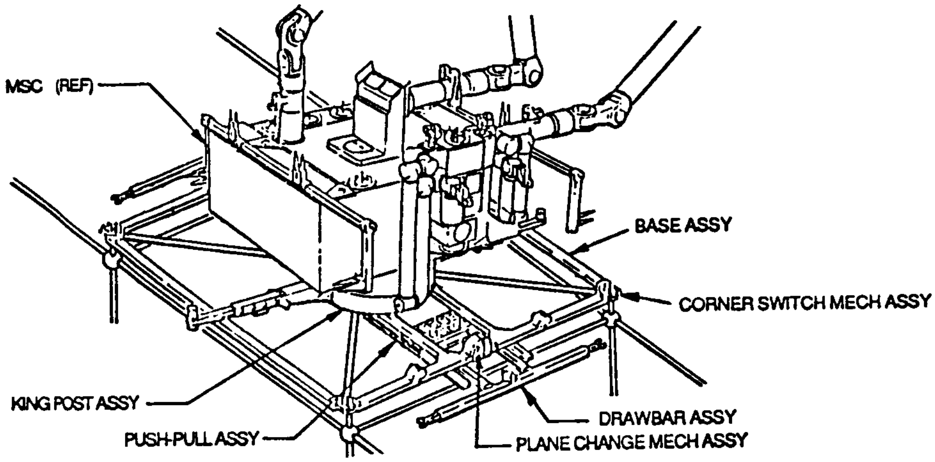

FIGURE 1- MOBILE TRANSPORTER AND MOBILE SERVICING SYSTEM

The MSC will be controlled either IVA from a pressurized module or by EVA from the MSC utility platform. Primary control is envisioned from the pressurized module. Since most of the MSC's functions are envisioned as being automatic, the need for EVA assistance during standard payload activities is minimized. One version has the Mobile Transporter operating in an independent mode without the need for attachment to, or control by an attached MSC structure. This could allow separate operations for the transporter as a "truck" to support various station operations.

As a servicing center, the MSC will provide other services to the payloads. Some of these services are: providing a support structure for the payloads during transportation, providing video and lighting for the verification of payload installation, maintenance and servicing tasks, providing manipulative arms for maintenance, servicing and refurbishment tasks, and providing checkout of the payload before deployment. These particular requirements have been subject to much discussion, as have others concerning operational speed, method of attachment, method of propulsion, degrees of freedom, controllability, autonomy, system mass, maintainability, and other factors, but we have used the above four requirements as a baseline for our discussion of various concepts.

EARLY MOBILE REMOTE MANIPULATOR SYSTEM (MRMS) CONCEPTS

Many concepts of manipulator propulsion to move about the surface of the space station have been analyzed and discarded for various reasons. A natural attachment and propulsion scheme has centered around a wheeled transporter traversing upon attached rails. While quite simplistic in nature, these concepts involve the attachment of a high-mass rail system at all points where the MSC is expected to operate. Curved rails or switches must be mounted at all turning and plane change locations. Even the variation of a monorail system requires an extensive rail system, and the high stresses applied to a single rail can bring total system mass up to that of a dual rail system to compensate in strength. Figure (2) depicts a typical railed transporter system.

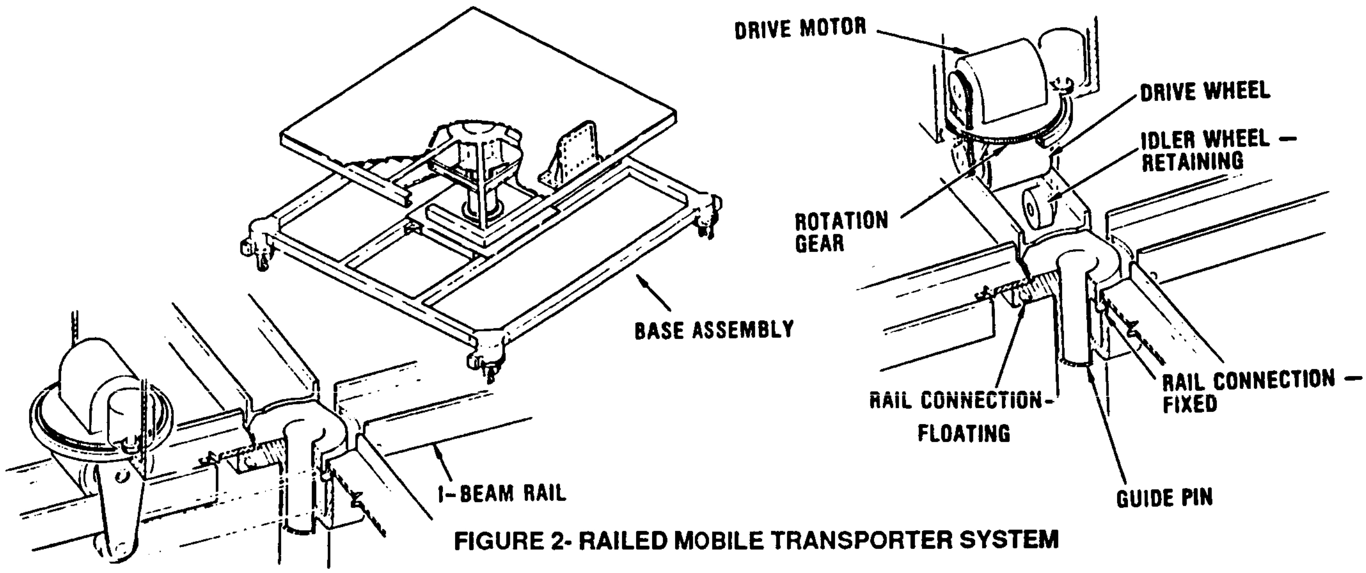

FIGURE 2- RAILED MOBILE TRANSPORTER SYSTEM

One solution to the massive rail dilema is to use transporter attachment points at the truss node fittings. Small knobs or rings can be "grasped" by the transporter system as it traverses each fitting point, thus saving the mass of continuous rails. The problem lays in how to design a mechanism that can successively grasp each node fitting for continuous travel on the truss surface, or for turning and changing planes, and yet have a secure attachment to the station structure. One concept used rings similar to boat oarlocks, with a small slot in the top, to allow javelin-shaped rails attached to a transporter base to pass through. The rings were drawn inward by a dis-continuous drawbar mechanism for traversing. Turns and plane changing was difficult with this concept. Figure (3) depicts the "javelin / ring" transporter concept.

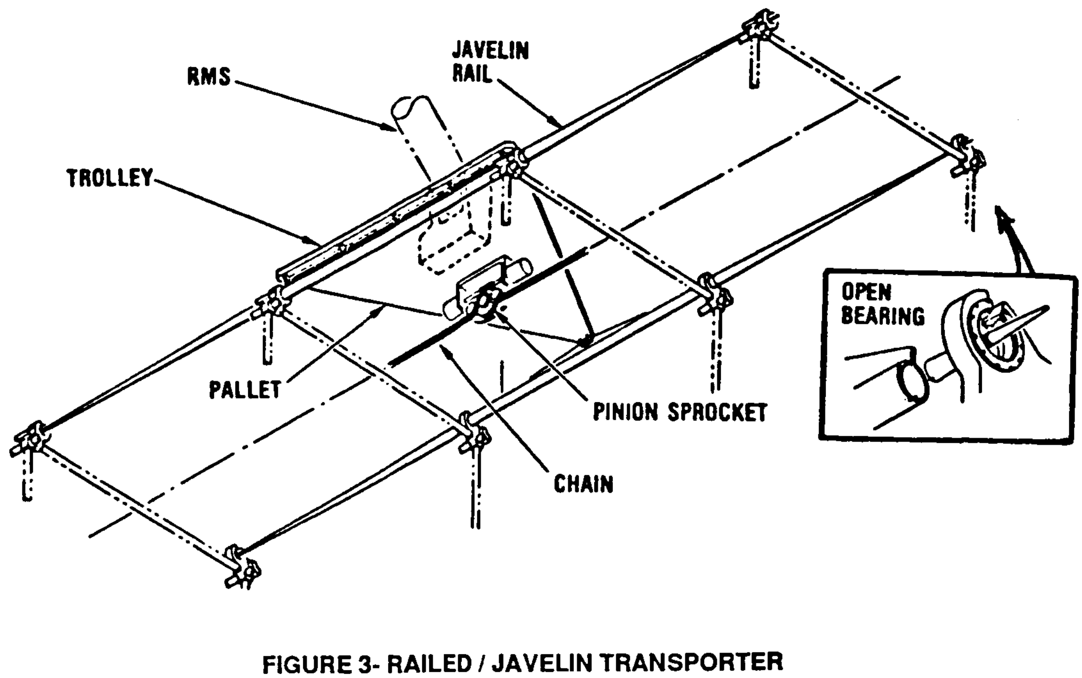

FIGURE 3- RAILED / JAVELIN TRANSPORTER

Later concepts centered on the use of 9cm diameter mushroom-shaped node "guide pins" developed by NASA Langley as the transporter attachment points. These 9cm high, 0.4 Kg pins are drawn through slotted rail assemblies in many concepts developed over the past two years, and remain the prime attachment scheme for most MSC systems under development. Many discontinuous and continuous motion drawbar transporter concepts, several endless belt crawler transporters, and an RMS-propelled transporter variation make use of these or similar pins for attachment. Figure (4) depicts the transporter node guide pin developed at NASA Langley.

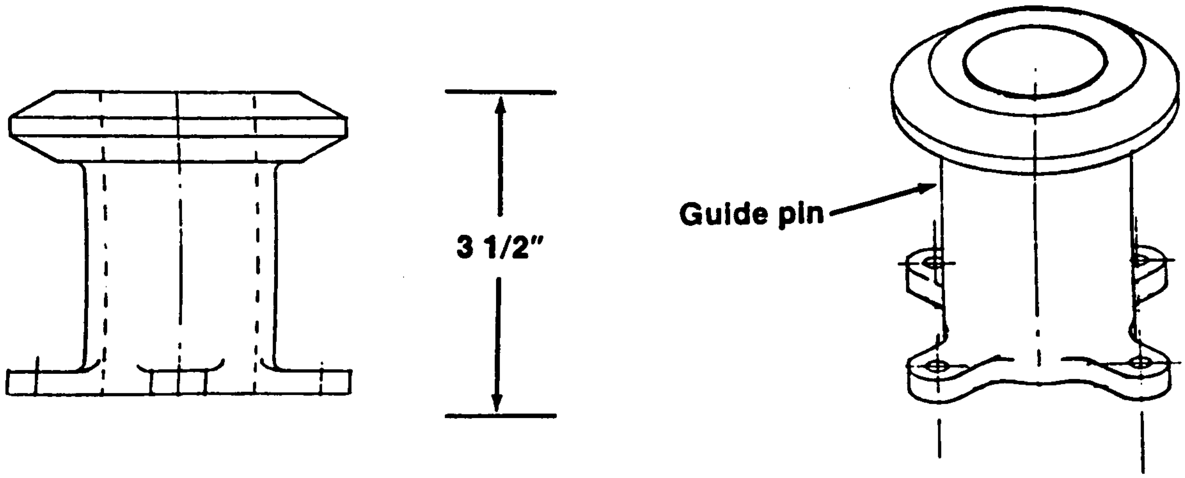

FIGURE 4- NASA MSC TRANSPORTER NODE GUIDE PIN

The use of the node guide pin scheme as an attachment point, and means of motivation for an MSC transporter, requires some sort of grasping mechanism for the widely spaced pins. Most concepts use a discontinuous motion to grab successive pins in the traversing motion. Dispensing with the idea of grasping robotic pincers reaching for the node pins, one concept made use of the cross-country ski traversing method of placing one ski after the other, with a special bottom coating to keep the ski from sliding back. The MSC transporter uses two sliding rails to surround each node guide pin, with an eccentric jamb bar or ratchet to hold each rail in position on the pins. Figure (5) illustrates this concept.

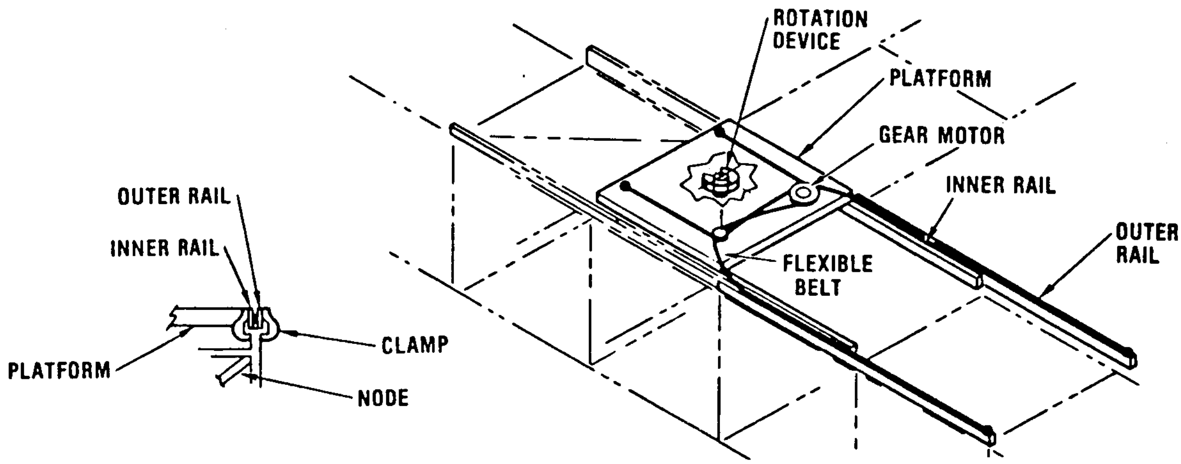

FIGURE 5- SLIDING RAIL MSC TRANSPORTER

NASA Langley determined that a continuous and firm attachment to the truss structure was of prime importance in the design of a mobile transporter. Using the mushroom-shaped guide pin shown in Figure (4) as an attachment base, Langley devised the push-pull transporter, (sometimes called the Track-layer) as a simple method of moving a manipulator system base about the truss surfaces. The push-pull transporter uses slotted rails through which the guide pin heads pass. A rack-and-pinion actuated , or similar mechanism drawbar mechanism reaches out, attaches to, and draws inward each successive node guide pin. The resulting motion is start/stop in action, but the required mechanisms are simple. In-plane turning is accomplished by the use of four "corner switches" that direct the motion of incomming node pins. The corner switches and drawbar mechanism are rotated 90°, and the guide pins are drawn inward from the new direction. Plane change is accomplished by truss-mounted "flip platforms" that rotate the transporter over the side of the truss structure. Figure (6) illustrates the Push-pull Transporter concept.

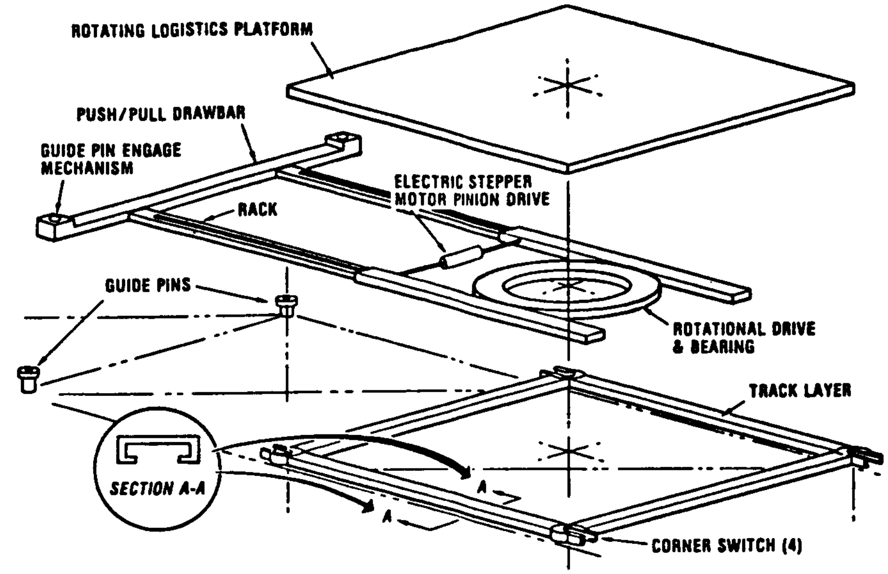

FIGURE 6- NASA LANGLEY PUSH-PULL MOBILE TRANSPORTER

Using the NASA Langley concept of solid attachment to the truss structure by having slotted rails securely surrounding the node guide pins, one improvement was to eliminate the discontinuous motion of the node pin drawbar assemblies. One concept makes use of dual endless toothed belts encased in split rail assemblies. The smooth, continuous motion belts grasp the "moving" pins and bring them into the slotted rail assemblies. Since this method can not make use of the corner switch direction-changing method, four forks grasp the base of the node pins, and the clamshell rails open to allow the transporter to be lifted off of the pins for turning by a turret assembly. Plane changing uses swiveling node pins or the plane change mechanisms mentioned later. The attachment is solid, and the motion smooth, but this concept uses fairly complex mechanisms. Figure (7) depicts the split rail crawler transporter.

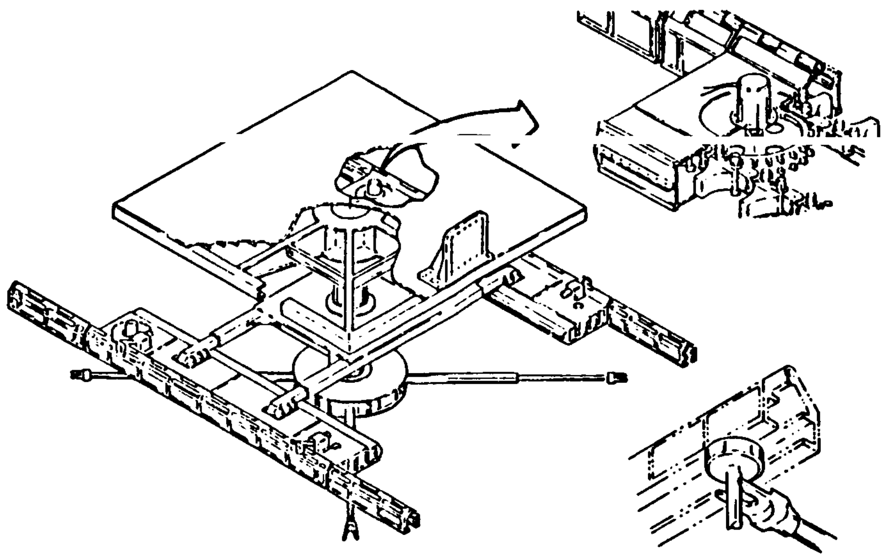

FIGURE 7- ENDLESS BELT SPLIT RAIL CRAWLER MOBILE TRANSPORTER

The complexity of some of the mobile transporter concepts caused many designers to take a long, hard look at ways to eliminate excess mechanisms. It was decided that the MSC contained an eloquent peice of machinery in itself,- the RMS manipulator arm. Why not use this already-developed device as the motion-producing mechanism for traversing throughout the station real estate? No plane change or direction changing mechanisms were required. The RMS-Propelled concept was born. This transporter concept moved along in "inch worm" fashion, -attaching, detaching, and re-attaching the end effector to produce traversing motion, plane-change, or turning. Later versions used a three or four point attachment fixture securely attached to the end effector for stiffness.

Problems arose in simulations with controlling such complex motion,- especially in turning and plane changes. Trying to attach and re-attach even a single point end effector became a control nightmare. The NSTS RMS, or even the re-designed SSRMS was not designed for this repeated operation. The standard NSTS RMS was difficult to reverse and use the end effector as an elbow joint for every other traverse step, and the end effector joint was too weak for large payloads when used as a "shoulder". Another problem was where did one place a payload of any size, batteries, and the EVA astronaut. Figure (8) depicts the RMS-Propelled "Inch-worm" concept.

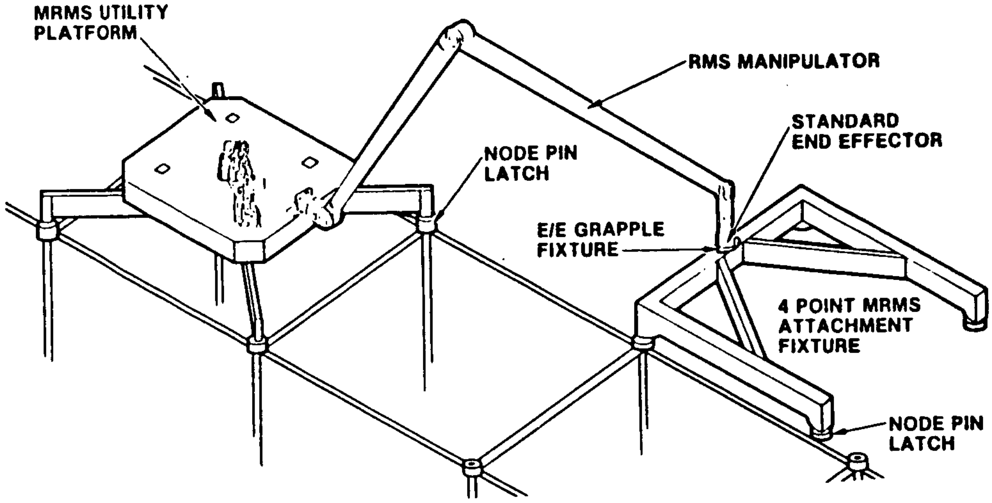

FIGURE 8- RMS-PROPELLED "INCH WORM" MSC TRANSPORTER

The requirements for a mobile transporter system were starting to be defined. Solid attachment, smooth motion, versitile functionality and low complexity driven by the number one factor- *low cost*, were the drivers that resulted in the dual push-pull transporter with on-board plane change mechanisms. The above-mentioned MSC transporter concepts seemed either too complex, poorly functional, or produced a discontinuous motion that disturbed the space station µG environment.

The Langley push-pull transporter seemed a good departure point, for it offered solid attachment to the truss at all times,- even during turning and plane change. The mechanisms were simple and could be made redundant for fail-safe operation. The transporter mass was low, and the base structure was adaptable to various configurations of MSC superstructure. The discontinuous motion produced by the drawbar assembly remained the design problem.

One has only to look at how you climb a ladder to envision how this motion can be smoothed out. You do not remove both hands from the ladder to reach for the next rung (at least not more than once). Each hand reaches for a new rung in a smooth, continuous motion as your body glides up the ladder. Your feet are doing this same motion at the other end. This concept was applied to the push-pull transporter with the drawbar split into two, separately-controllable node-pin grasping drawbars. The uneven stress of having only one node pin attached remained a problem. Figure (9) depicts the Split Dual Drawbar concept.

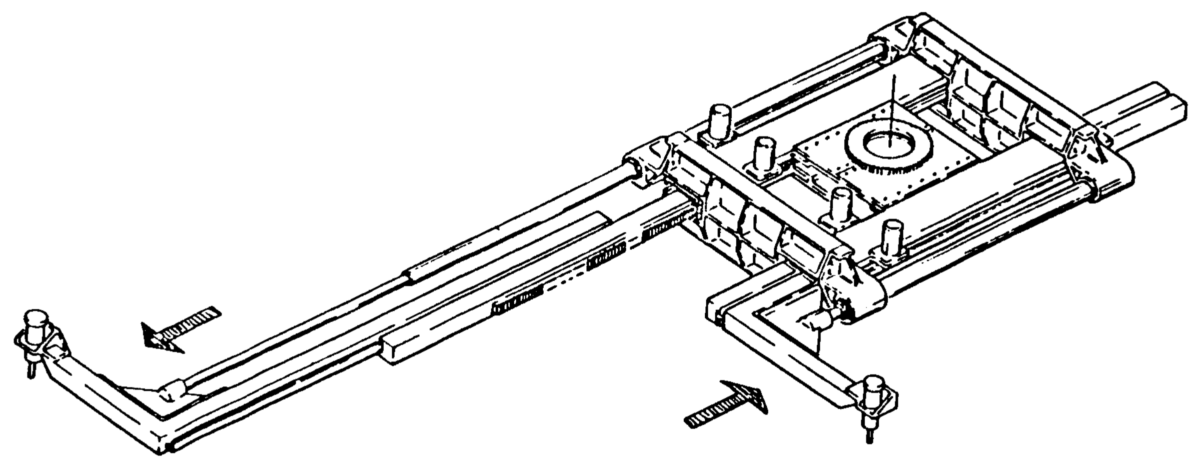

FIGURE 9- SPLIT DUAL DRAWBAR TRANSPORTER CONCEPT

The uneven stress that a single attachment point drawbar has on the truss members and the transporter body itself was the main driver to add a second dual drawbar assembly to the push-pull concept. This second assembly created a more massive transporter, but these more rigid drawbars did not twist the truss structure on traverse, and control was the same. This second drawbar assembly is placed at the other end of the transporter, with the wider bars of one fitting outside the narrower bars of the other. The dual drawbar design uses the same corner switches as the Langley concept, but this design does not require a slot in the top for a guide pin withdrawal pin to slid into. The guide pins are grasped below the node guide pin head by retractable fork assemblies. It is these retractable forks that allow the drawbars to rotate beneath the slotted rails and the guide pin heads. Plane change mechanisms mounted on the sides of the slotted rail assemblies allow plane change maneuvers at any clear point on the truss structure. Figure (10) depicts the basic dual-drawbar mobile transporter concept.

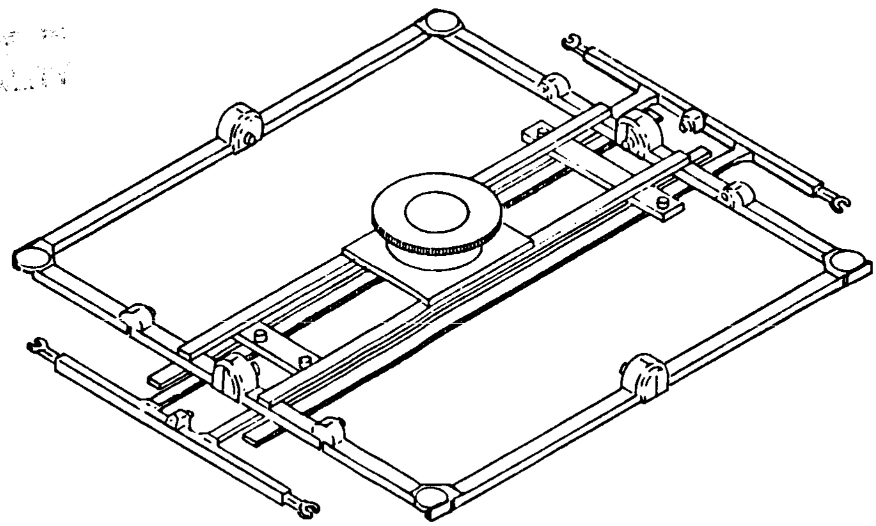

FIGURE 10- DUAL DRAWBAR PUSH-PULL MOBILE TRANSPORTER

Let's show a little more detail on how this design works and how it differs from the others. This basic design will work for an Independently-Controlled Mobile Transporter (ICMT), as well as the Mobile Transporter for the Canadian-supplied MSC System. The addition of a battery system, internal and EVA controls, a thermal control system, and a control link to the station, can create an independent transporter system able to function away from the MSC. Figure (11) depicts the functional layout of this concept.

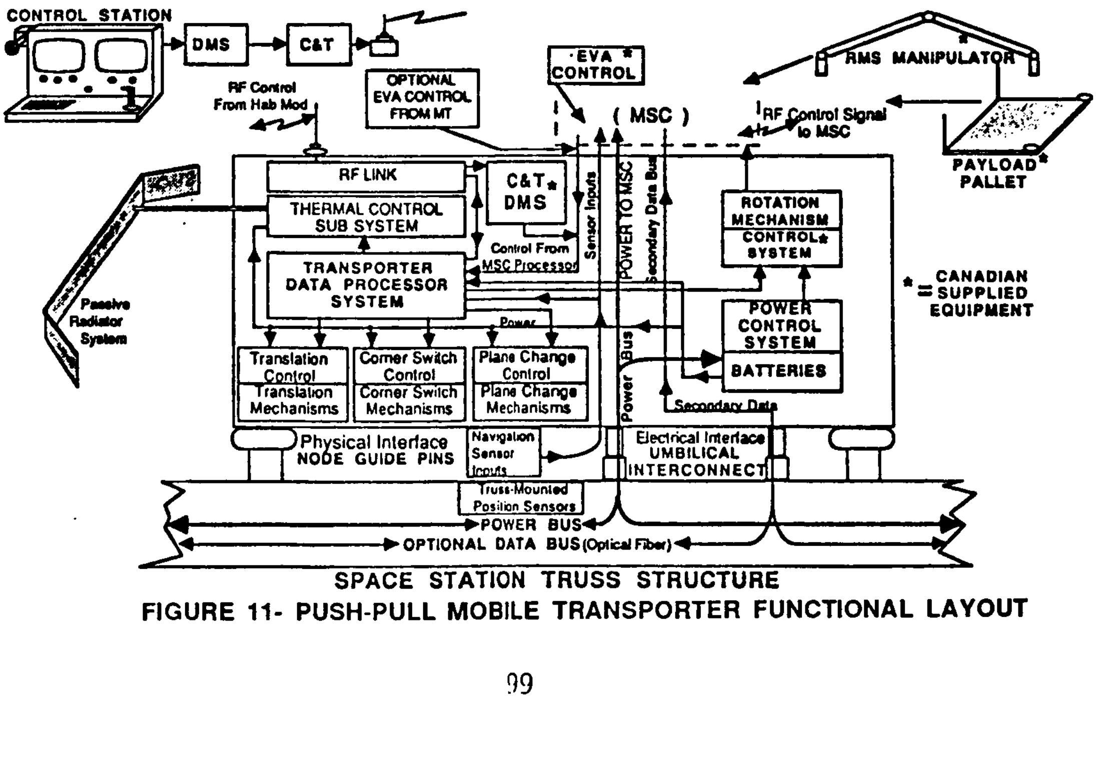

FIGURE 11- PUSH-PULL MOBILE TRANSPORTER FUNCTIONAL LAYOUT

The independent controllability feature of this mobile transporter concept will allow the MSC to function as a separate entity in manipulative operations, as well as the transporter. These two separate major subsystems of the MSC System contain the battery / PMAD systems to afford operations away from the station power bus. Charging for both power systems is normally accomplished through the Mobile Transporter umbilical connection to the station, but the MSC can be connected directly for charging or independent operations. DMS and control information is also available at these umbilical ports.

SPACE STATION DUAL PUSH-PULL MSC MOBILE TRANSPORTER CONCEPT FEATURES

Some of the features that have made the dual push-pull concept desirable are the self-contained plane change mechanisms, the dual drawbars for eliminating discontinuous motion, and the drawbar fork assemblies that allow easy rotation and simple corner switch construction. These features help bridge the gap between that basic driver,- *COST*, and achieving the goal of functionality.

Having to rely on dedicated plane change mechanisms attached to various locations on the space station was self-defeating in two aspects. The mass and resulting cost was a negative feature, and the MSC / transporter was constrained to these operations only at points where the mechanism was installed. Some of these location-dependent mechanisms included "flip platforms" to allow the transporter to drive itself over a 90° edge of the truss, and dedicated swivel node guide pins that were driven by actuators on-board the transporter. It became apparent that all plane change functions should be accomplished by an on-board mechanism. The most successful of these has been the rotating slotted rail section plane change mechanism depicted in Figure (12) and used on the dual push-pull transporter.

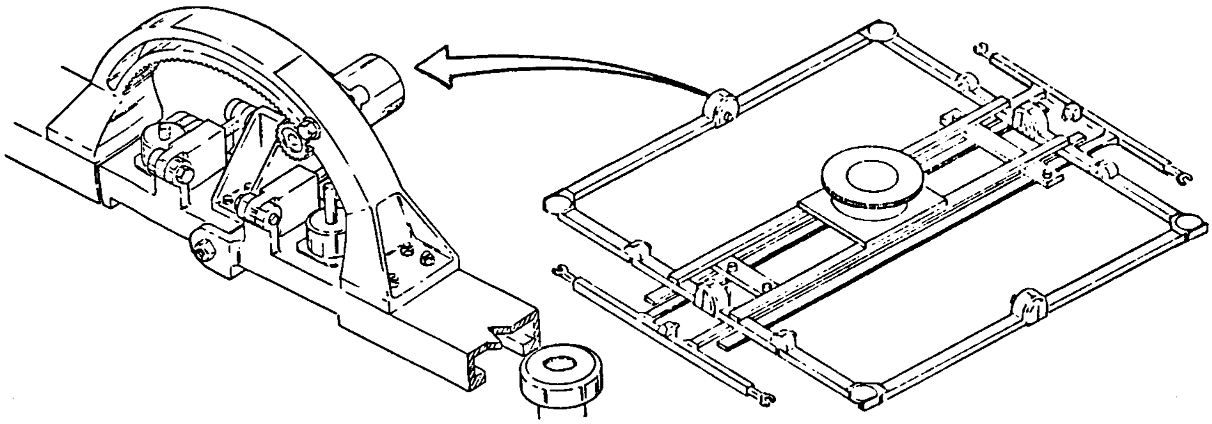

FIGURE 12- SELF-CONTAINED MOBILE TRANSPORTER PLANE CHANGE MECHANISM

Plane change is accomplished in the following manner:

(a) At the desired point on the truss structure, the transporter makes a 90° turn maneuver. Actually, the transporter base / MSC remains in the same orientation, and only the drawbar and corner switch are rotated to the new direction.
(b) One drawbar / fork assembly attaches itself onto the set of guide pins on the side of the truss oposite from where the transporter is to maneuver to.
(c) This drawbar actuated by a rack-and-pinion, or similar actuator, drives the transporter halfway off the edge of the truss until the plane change mechanism straddles the other set of guide pins.
(d) With one half of each P/C mechanism firmly locked onto the two "top" guide pins, the other half of the mechanism, with the guide pin lock jaws open, rotates 90° to enclose the other pins on the new truss face. The guide pin jaws now lock onto these pins. The transporter has not rotated at this time,- only one half of the P/C mechanism.
(e) With the four guide pins securely attached to the P/C mechanism, the drawbar forks retract to release the other two guide pins. The drawbar retracts into the transporter.
(f) At this point, the transporter is rotated 90° by the plane change mechanisms.
(g) The opposite drawbar reaches out to the other two guide pins and the forks attach.
(h) The "original half" of the P/C mechanism opens and releases the "top" guide pins, rotates 90°, and the other half of the mechanism releases the other two guide pins.
(i) The drawbar now retracts the transporter onto the new truss face, and a turn maneuver is made to traverse on the new plane, or the maneuver is repeated for traverse on the "back" side.

In spite of the seemingly complex set of steps, this maneuver can be under total automatic sequence control, as all of the guide pins are found in the same orientation and location. Positional feedback on the actuators, and sensors in the fork grippers and plane change mechanisms can verify compliance with a pre-programmed maneuver sequence. These P/C mechanisms weigh less than 20Kg each, compared to hundreds of Kg in large dedicated platforms. Dual mechanisms, each with dual drives, and emergency manual actuation, provide reduncancy for fail-safe operations. The low mass / compact design, with easy access to EVA activities, provides for on-orbit replacement in maintenance operations.

The split drawbar mechanism depicted in Figure (9) has evolved to the present concept of a forward and aft set of drawbars. A unique feature that arose from this dual configuration is the retractable forks on the drawbars. Besides allowing engagement / disengagement from the base of the guide pins, this arrangement allows the drawbar assembly to be placed <u>below</u> the corner switch / rail assemblies. Not only does this arrangement provide for a compact transporter, but pin engagement <u>below</u> the guide pin head, rather than at the <u>top</u>, does not require a slot in the <u>top</u> of the corner switch. The corner switch structure is already somewhat weakened by the slot in the <u>bottom</u> through which the node guide pin passes.

The feature of having a smooth, continuous motion is accomplished at the expense of having an extra drawbar assembly. Analyses have shown that a smooth acceleration to operating speed, a continuous traversing motion, and a smooth deceleration to a stop, have a dramatic effect on eliminating unnecessary μG levels. Figure (13) shows the smooth "ladder climbing" motion of the MT traverse.

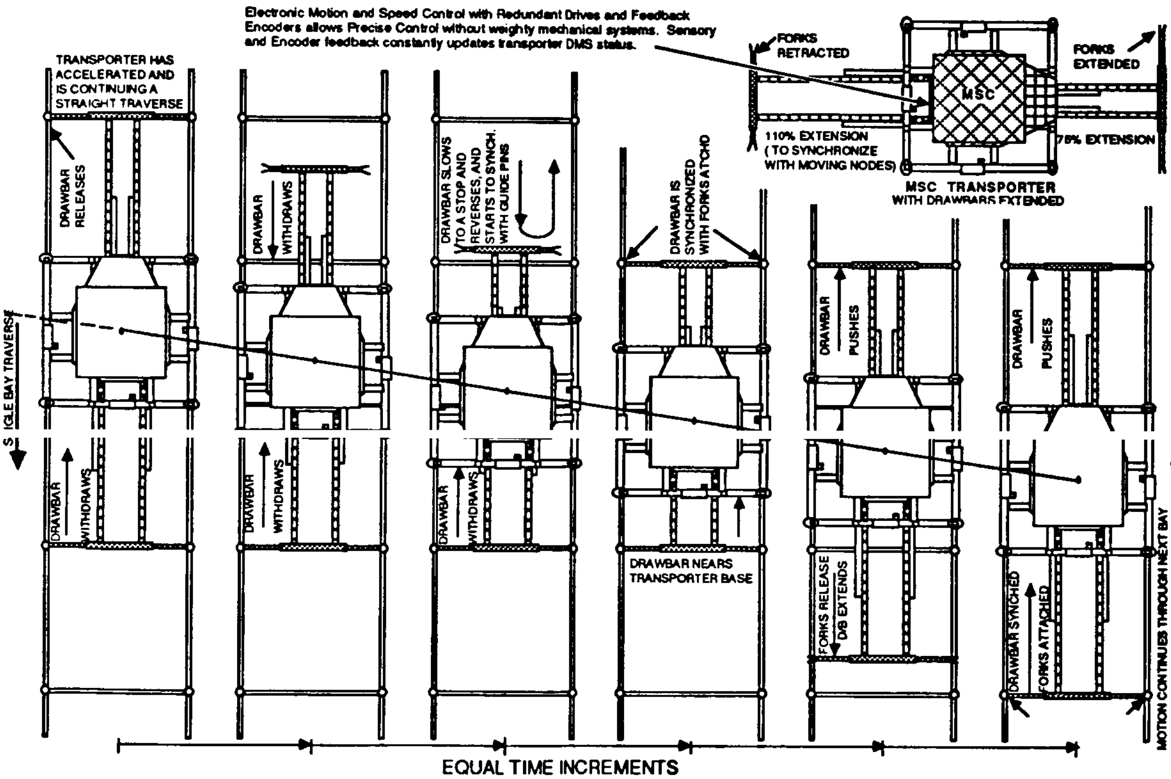

FIGURE 13- MOBILE TRANSPORTER DUAL DRAWBAR PRODUCES CONTINUOUS MOTION

Much design effort remains to create the fully-functional transporter system required for the space station. Co-ordination of the mechanical drives for synchronized motion in the traverse, interconnection of corner switch and plane change mechanisms in <u>*triple redundancy*</u> for fail-safe reliability, and the integration of a complete, self-contained transporter with the Canadian Mobile Remote Servicer for independent operations will require intense engineering efforts. Many NASA centers and contractors have collaborated to produce well thought designs to solve the manipulative and robotics requirements for the initial operational and growth configurations space stations. This paper has only touched on some of the major factors that were considered in the development of the preceeding Mobile Transporter concepts.