Umbilical Mechanism Assembly for the International Space Station

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Abstract

Mechanisms for engaging and disengaging electrical and fluid line connectors are required to be operated repeatedly in hazardous or remote locations on space station, nuclear reactors, toxic chemical and undersea environments. Such mechanisms may require shields to protect the mating faces of the connectors when connectors are not engaged and move these shields out of the way during connector engagement. It is desirable to provide a force-transmitting structure to react the force required to engage or disengage the connectors. It is also desirable that the mechanism for moving the connectors and shields is reliable, simple, and the structure as lightweight as possible.

With these basic requirements, an Umbilical Mechanism Assembly (UMA) was originally designed for the Space Station Freedom and now being utilized for the International Space Station.

Introduction

The Umbilical Mechanism Assembly (UMA) consisting of an active half and a passive half provides the capability to remotely engage electrical umbilical connectors on various space station subsystems.

One of these subsystem is the Mobile Transporter (MT). The MT provides the capability of moving the Mobile Remote Servicer (MRS) and payloads to discrete locations along the station truss for assembly and maintenance operations. The UMA will be used to connect the electrical power umbilical from the truss segments to the MRS.

This paper is written to provide an overview of the UMA and describes its features and capabilities. Kinematics of the mechanisms and details of various assemblies are provided. Criteria for calculating the actuation load is defined. Results and lessons learned from the development test are addressed.

Summary

The UMA automatically connects and disconnects electrical umbilical contacts while shielding the electrical connectors from debris. The mechanism reacts mating and demating loads internally, without additional supporting structures. The mechanism is designed for service in outer space, where its shields would protect against micro meteoroids, debris, and ultraviolet radiation.

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The mechanism consists of an active and a passive assembly. It can accommodate an initial linear misalignment of 6.35 mm (0.25 in) and an angular misalignment of 2° between the active and passive assemblies.

All functions -- extension of the plug, mating, and movement of the debris shield -- are actuated by a single drive mechanism with redundant motors. An override feature in the drive train allows manual operation in case of motor failure.

UMA Features and Capabilities

Key features and capabilities of the UMA are as follows:
- Remotely connect umbilical connectors for the transfer of power and data for multiple applications on International Space Station
- Accommodate an initial linear misalignment of 6.35 mm (0.25 in) and angular misalignment of 2° between the active and passive assemblies
- Provide capability for on-orbit replacement
- Envelope of the active half is 29.21 x 34.29 x 35.56 cm (11.5 x 13.5 x 14 in) and passive half is 26.92 x 28.70 x 17.78 cm (10.6 x 11.3 x 7.0 in)
- Connector mating force of 1112 N (250 lbf) minimum
- Design life cycles - 5000
- Capability provided for Extravehicular Activity backup
- Male and female connectors are protected from external debris
- Weight of active half is 32.0 kg (70.4 lb) and passive half is 6.7 kg (14.7 lb)
- Electrically single failure tolerant
- Mechanically zero failure tolerant and designed to minimum risk
- Operate in vacuum in a temperature range of -78.9 to 60 °C (-110 to +140 °F) environment
- Withstand launch on the Space Shuttle in an acoustic vibration environment of 13 grms in a frequency range of 25 to 2000 hertz

Design Factors

The mechanical components of the UMA were analyzed for structural strength to meet the following Space Station requirements:

Safety factors
On-orbit	Limit = 1.1 x maximum design load
	Ultimate = 1.5 x maximum design load
Launch	Limit = 1.0 x maximum design load
	Ultimate = 1.4 x maximum design load

The UMA is designed to withstand ultimate load of 5671 N (1275 lbf) connector mating load.

UMA Description

The UMA shown in Figure 1, is a lightweight and reliable mechanism that provides for automatic mating and demating of a pair of connectors.

The electrical connector (receptacle) lies within a passive assembly while an electrical connector (plug) lies on a movable carrier in an active assembly. Major components of the UMA active and passive assemblies are shown in Figure 2 and Figure 3, respectively. A motor-driven mechanism translates the carrier down on two Acme drive screws to mate the connectors. As the carrier moves down, it rotates a pair of pivoting covers at the lower end of the active half, moving them out of the way of the carrier. As the covers pivot down, receptacle and plug respectively on the movable members and on the passive half engage (see Figure 4). Mating and demating forces are reacted between the passive half housing and active half housing through the movable covers, which avoids the need for an additional rigid connecting structure.

The movable covers not only transmit mating and demating forces, but also provide coarse alignment of the connectors prior to mating. A pair of shield on the passive half cover the lower connector prior to mating. The lower connector is mounted on four stacks of Belleville washers allowing shift and tilt to align the connectors as they mate. A manual override mechanism is provided on the UMA active half to operate the mechanism in case of motor failure.

A set of launch restraint mechanism on each side of the active half secures the active half body against the substructure during the launch environment and until in position on orbit. The restraints are released (single function) during the initial actuation of the active half.

The active half is powered by functionally redundant Integrated Motor Controller Actuator (IMCA) and controlled through a MIL-STD-1553 data bus. The IMCA is commanded to actuate the UMA and engage the plug with the receptacle when the UMA active half is within the engagement envelope of the passive half. Another command to the IMCA retracts the connector carrier and uncouples the connector.

Kinematics

The mating sequence is shown in Figure 5 and consists of the following steps:

a) Upon receipt of an electrical signal through the data bus, the IMCA drives a gear train that turns the drive screws and begins to extend the connector carrier of the active half.

b) A cam surface on the carrier begins to open the debris shield doors of the active half. As these doors approach the end travel, they engage the passive half housing through four probe/drogue interfaces.

c) The carrier continues to extend and contacts strikers on a set of linkages that open the passive half debris shields. The operation is completed as the pins in the male

electrical connector are inserted into the sockets in the receptacle on the passive half.

d) Redundant position sensing through limit switches is incorporated to stop the connector carrier at predetermined engage and disengage positions. In case of limit switch failure the IMCA motor control software will turn off the motor when a predetermined turn-count is reached. A hard stop is also provided at either extreme position and the motor torque is limited so that contact with the hard stop cannot induce motor burn-out or cause mechanical failure of any UMA component.

UMA Assembly Details

Structural Compliance System
The active half is suspended on the primary structure on four helical springs. These springs deflect in the axial and or lateral directions and allow the active half to achieve structural compliance with the rigidly mounted passive half.

Carrier Cam Operation and Interaction with the Debris Shields
The carrier contains the electrical plug and translates up and down on two drive screws. Each drive screw is attached on the active half body in a gimbal bearing at the upper end and on a thrust bearing at the lower end.

On each side of the carrier there are two 'L' shaped cam profiles shown in Figure 6. These cams operate a set of debris shield doors. While translating downwards, the carrier (prior to engaging the electrical connectors) contacts debris shields linkage on the passive half and opens them. As the carrier translates downward on the drive screws, the doors gradually open drogues on each door and engage with probes on the passive half. The cams also transmit sufficient force to align the active half with the passive half as the probes seat in the drogues. The probe and drogue interaction subsequently provide the load reacting link between the active and passive half when the pins in the plug are inserted into the receptacle in the passive half.

The electrical receptacle is attached on the passive half on four stacks of Belleville disk springs shown in Figure 3. These spring stacks allow the receptacle to shift sideways and tilt slightly to achieve final alignment with the plug and limit the pin insertion load on the plug.

Power Train
The drive screws are single start, 1.27 cm (0.5 in) in diameter and have 3.94 threads per centimeter (10 threads per inch) pitch. These screws are operated from a gear box having 8.3:1 reduction from the motor input through three spur gear meshes. The gears are design per American Gear Manufacturer's Association (AGMA) class 10 specification and are made from Nitraolly 135 M. The gear teeth surface is nitrided for wear resistance to Rockwell hardness 30-36. For corrosion protection, the gears are cadmium plated. Everlube 620 dry film lubricant is used for lubrication. Each gear is mounted in a set of sealed ball bearings.

Launch Restraint System

Two launch restraint mechanisms shown in Figure 7 are attached on each side of the active half to secure it against the substructure during the launch environment.

Each launch restraint system consists of a spring loaded pivoting housing and a set of restraint pins connected on a bellcrank linkage system. In the launch configuration the pins are engaged in the pivoting housing while the bellcrank is in contact with the carrier and the linkage system is in the overcenter position. As the carrier moves downward, the bellcrank linkage system pulls the restraint pins out of the housing, the housing pivots away from the guides and the active half is then able to achieve compliance with the passive half.

Actuation Loads

The UMA mechanism requires less than 6 in-lb of actuation torque to provide a minimum connector preload of 1112 N (250 lb). The actuation system provides more than 100% torque margin relative to the torque available from the actuator [(2.05 N•m) (18 in•lbf)].

The efficiency of the drive screw is a critical parameter in sizing the UMA actuator and the structure. The actuator was sized for worst case load with the worst case drive train efficiency. The efficiency of the screw threads varies with the coefficient of friction and the thread geometry. The mechanism structure was sized to withstand a jamb condition with the highest actuation torque at the greatest drive train efficiency.

The overall efficiency of the screw is based on the following relationship (derivation is found in Appendix I) and the friction versus efficiency is shown in Figure 8.

$$F = \frac{Eff_s}{1 + Eff_s \cdot (r_t \cdot \mu) \cdot 2\pi/L} \cdot \tau_{app} \cdot 2\pi/L \qquad (1)$$

Loading efficiency is based on coefficient of friction of 0.2 and 0.5 and from the above figure it is found to be between 0.114 and 0.244 (2)

Actuator Loads at Gearbox inputs

The best and worst case efficiencies of the gearbox are based on 1% to 3% efficiency loss per stage. This results in an overall efficiency of between 91% to 97%.

The UMA actuation loads come from three sources, namely alignment load, passive half cover actuation load, and load form connector seating/preloading. The largest being the connector seating/preloading load of 1112 N (250 lb).

Each isolator spring has a spring rate of 4378 N/m (25 lb/in) and may deflect as much as 1.27 cm (0.5 in), therefore, the alignment load is:

$$4 \cdot 0.0127 \text{ m} \cdot 4378 \text{ N/m} = 222.4 \text{ N (50 lb)} \qquad (3)$$

The torque required to achieve alignment with these springs was found to be insignificant with respect to the torque required for connector seating/preloading Similarly the torque required to actuate the passive half debris shields was also found to be insignificant.

The mechanical advantage and efficiency of each stage of the drive train and the efficiency of the drive screw were taken into account for developing the actuator torque. The maximum drive screw torque required (with low screw efficiency) is based on the following relationship:

$$T = \frac{P \cdot L}{2 \cdot \pi \cdot Eff} \tag{4}$$

$$\frac{1112 \cdot 0.00254}{2 \cdot \pi \cdot 0.114} = 3.945 \text{ N·m (34.9 in·lbf)} \tag{5}$$

Where:
T = Actuator torque
P = Maximum load for connector seating/preload
Eff = Worst-case screw efficiency (0.114)
L = screw pitch

The maximum actuation torque is further reduced by 8.3:1 gear ratio, but slightly increased by the worst case gear train efficiency (91%). Therefore, the actuation torque is:

$$\frac{3.945}{8.3 \cdot 0.91} = 0.4325 \text{ N·m (4.62 in·lbf)} \tag{6}$$

The UMA drive train efficiency can vary over a range of more than two to one. This compounded by the torque limit tolerance of 10% of the actuator and results in the possibility that as much as 3736.5 N (840 lbf) can be transmitted to one of the nuts under some mechanism jamb conditions. Therefore, the UMA components are sized to withstand this jamb load.

Development Test

Development test was planned in the early phase of the design to characterizing and verifying the performance of the UMA, but also to gain information and experience on as many elements of the design as possible. Initial testing began on July 1,1991

Primary objectives of the test were to:

Evaluate performance characteristics at ambient and cold vacuum environments
Demonstrate cycle performance equal to twice the space station life
Demonstrate launch survivability in a space shuttle random vibration environment

As the test progressed, provisions were made to asses/observe additional aspects of the tests to achieve maximum return from the program. Specifically, a separate test was conducted to select a suitable dry film lubricant on the drive screws.

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Test Results

Development testing was completed in June 1993. All objectives of the test were met.

1. The structural compliance capability was verified at both ambient and cold temperature thermal vacuum environments. During performance testing the connectors were successfully mated with all possible worst case out-of-alignment conditions between the active and passive halves.

2. Completed over 11,000 life cycles which represented twice the on-orbit estimated operations.

3. During the initial performance test it was found that the Everlube 620 dry film was wearing off the drive screws and galling the threads.

4. During vibration testing the launch restraints prematurely actuated due to inadvertent movement of the carrier.

5. The original suspension springs were found to be very stiff and caused excessive distortion of the passive half structure.

Lessons Learned and Design Refinements

The following modifications were incorporated to resolve deficiencies noted in items 3, 4 and 5 of the above results

1. Everlube dry film lubricant on the drive screws was replaced with Tiolube which was found to provide better performance in a separate test. The installation of the drive screw was also modified with thrust bearings on the lower end and gimbal bearings at the upper end of each drive screw. The UMA mechanism with the new dry film lubricant and bearings was retested during the life cycle test. Test showed that the reported wearing and galling problem was corrected and reduction in the motor torque was achieved.

2. To prevent premature movement of the carrier in the random vibration environment, four spring-loaded plungers on the active half were installed to interface with detents on the carrier (Figure 6). This arrangement was successfully retested without any anomalies.

3. The suspension springs were replaced with more compliant springs and subsequent tests did not show any significant distortion of the passive half structure.

Conclusion

The UMA meets all performance requirements. The design of the UMA is mature and the flight hardware is in final fabrication while the qualification testing is expected to be completed in September 1996. The mechanism will be qualified to operate on orbit in a thermal vacuum environment. This mechanism can be used in various other applications for umbilical connections of electrical, data, video, fiber optics or fluid lines.

Acknowledgment

This work was performed under contract HX3200 Boeing Defense & Space Group, Houston TX.

References

1) UMA, Structural Integrity Report, MDC95H0423
2) Umbilical Mechanism Analysis Report, MDC 93H0428
3) UMA, Configuration Item Specification, SP-M-601

Appendix I

The expression for drive screw nut force for a given torque across the screw threads is:

$$F = Eff_s \cdot \tau_s \cdot 2\pi/L$$

Where the thread efficiency is given by:

$$Eff_s = \frac{\cos(\alpha) - \mu \cdot L/(\pi \cdot D_m)}{\cos(\alpha) + \mu \cdot \pi \cdot D_m/L}$$

given:

α = Angle

μ = coefficient of friction

L = Screw Lead, inches per thread

D_m = Diametral Mean of the screw

τ_s = Torque across screw threads

For a perfectly efficient ten threads per inch screw, the relationship between nut force and the torque across the screw threads is:

$$F = Eff_s \cdot \tau_s \cdot 2\pi/L = 1.0 \cdot \tau_s \cdot 2\pi \cdot 10$$

However, the ten threads per inch UMA Acme Screws operate between 12% and 25% power transmission efficiency due to thread and thrust bearing friction. At this low efficiency, the screw is irreversible.

Including the thrust bearing friction effects into the overall efficiency factor complicates the equations slightly. However, it can be seen from the results that in the screw efficiency regime that we operate in that the overall efficiency is insensitive to bearing friction.

The thrust bearing friction torque is proportional to axial force on the screw.

$$\tau_f = r_t \cdot \mu_t \cdot F$$

Where the applied torque is the sum of both the torque applied at the nut and the thrust bearing friction torque.
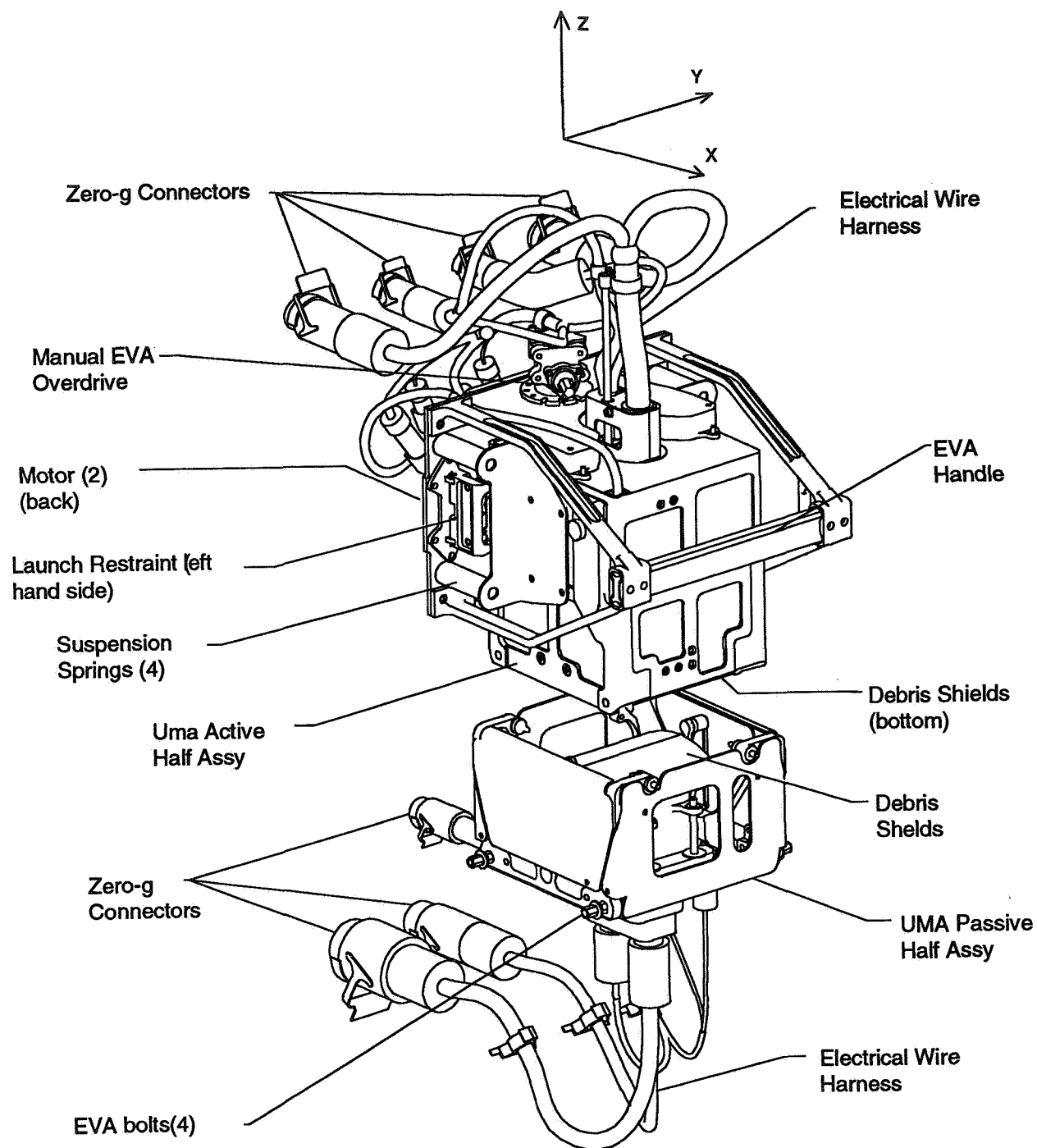
$$F = Eff_s \cdot \left(\tau_{app} - \tau_f \right) \cdot 2\pi / L$$

$$F = Eff_s \cdot \left(\tau_{app} - r_t \cdot \mu_t \cdot F \right) \cdot 2\pi / L$$
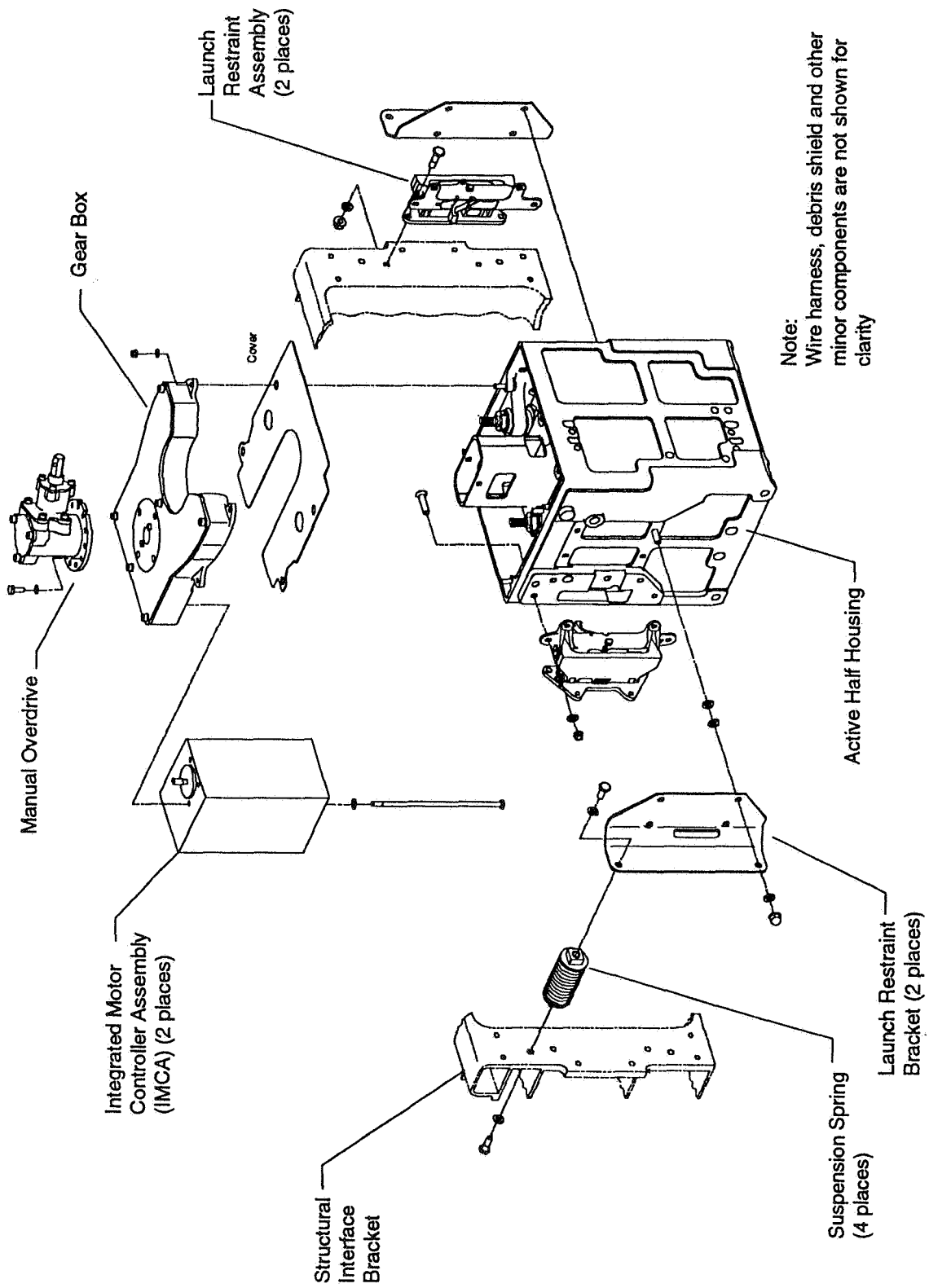
Solving for F

$$F = \frac{Eff_s \cdot \tau_{app} \cdot 2\pi / L}{1 + Eff_s \cdot \left(r_t \cdot \mu \right) \cdot 2\pi / L}$$

Arranging the equation screw efficiency as a function of coefficient of friction is

$$F = \frac{Eff_s}{1 + Eff_s \cdot \left(r_t \cdot \mu \right) \cdot 2\pi / L} \cdot \tau_{app} \cdot 2\pi / L$$

Z

Y

X

Zero-g Connectors

Electrical Wire Harness

Manual EVA Overdrive

EVA Handle

Motor (2) (back)

Launch Restraint (left hand side)

Suspension Springs (4)

Debris Shields (bottom)

Uma Active Half Assy

Debris Shelds

Zero-g Connectors

UMA Passive Half Assy

Electrical Wire Harness

EVA bolts(4)

Figure 1
Umbilical Mechanism Assembly (UMA)
Active and Passive Halves

Launch
Restraint
Assembly
(2 places)

Gear Box

Manual Overdrive

Cover

Note:
Wire harness, debris shield and other
minor components are not shown for
clarity

Integrated Motor
Controller Assembly
(IMCA) (2 places)

Active Half Housing

Structural
Interface
Bracket

Suspension Spring
(4 places)

Launch Restraint
Bracket (2 places)

Figure 2
Components of UMA Active Half

Housing

Debris Shield

Belleville Washer
Stack (4 places)

Electrical Plug

Alignment and
Latch Pin (probe)
(4 places)

Cover
(2 places)

External Zero 'G'
Connecector
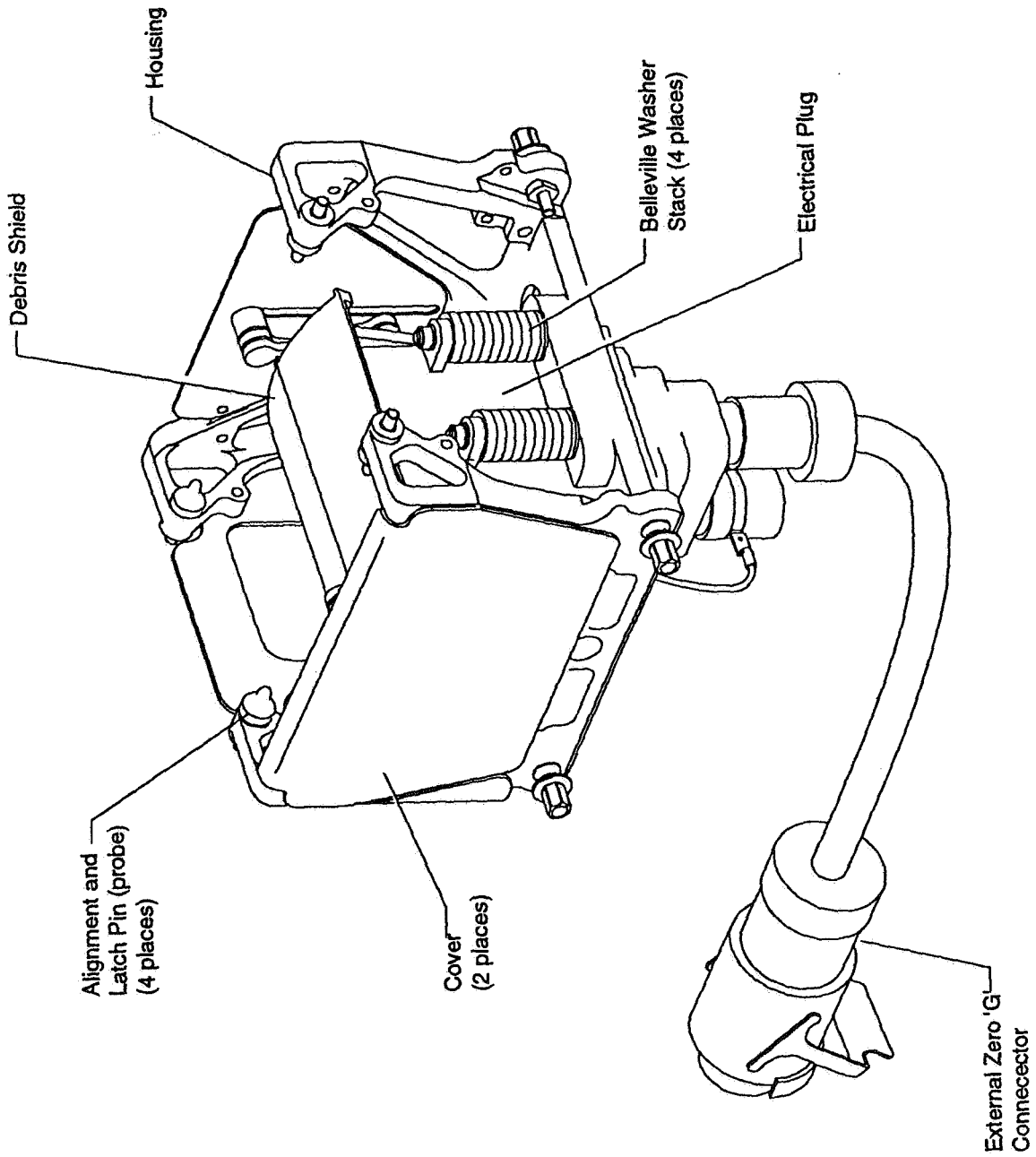
Figure 3
Component Details of UMA Passive Half

Active half debris shield
open and latched on the
passive half

Active half debris shield
pins following cam
surface on the carrier

Probe/Drogue
Interfaces

Electrical
Receptacle

Note:
Covers of UMA passive half
housing are not shown for
clarity
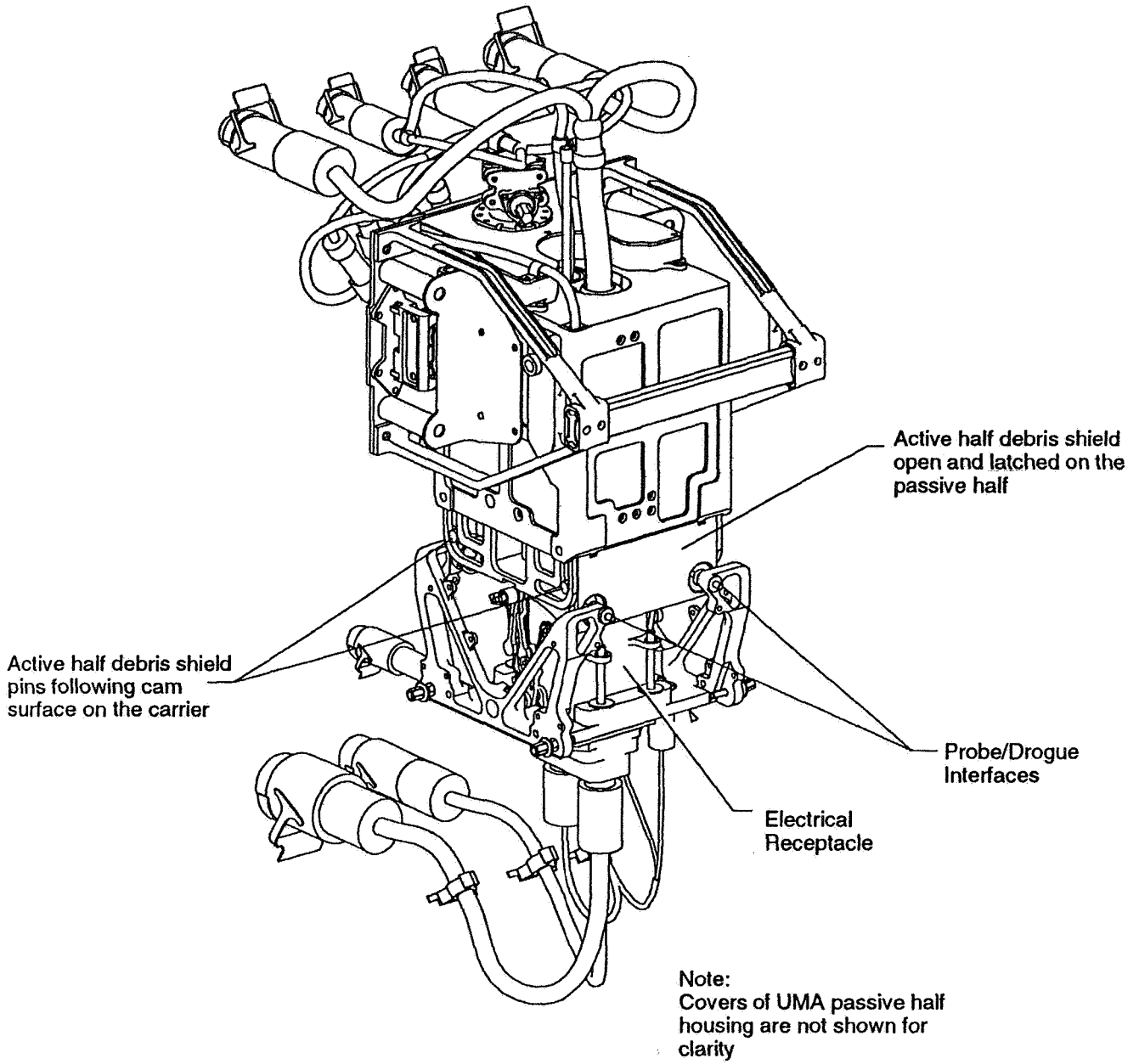
Figure 4
UMA active and passive halves in latched configuration
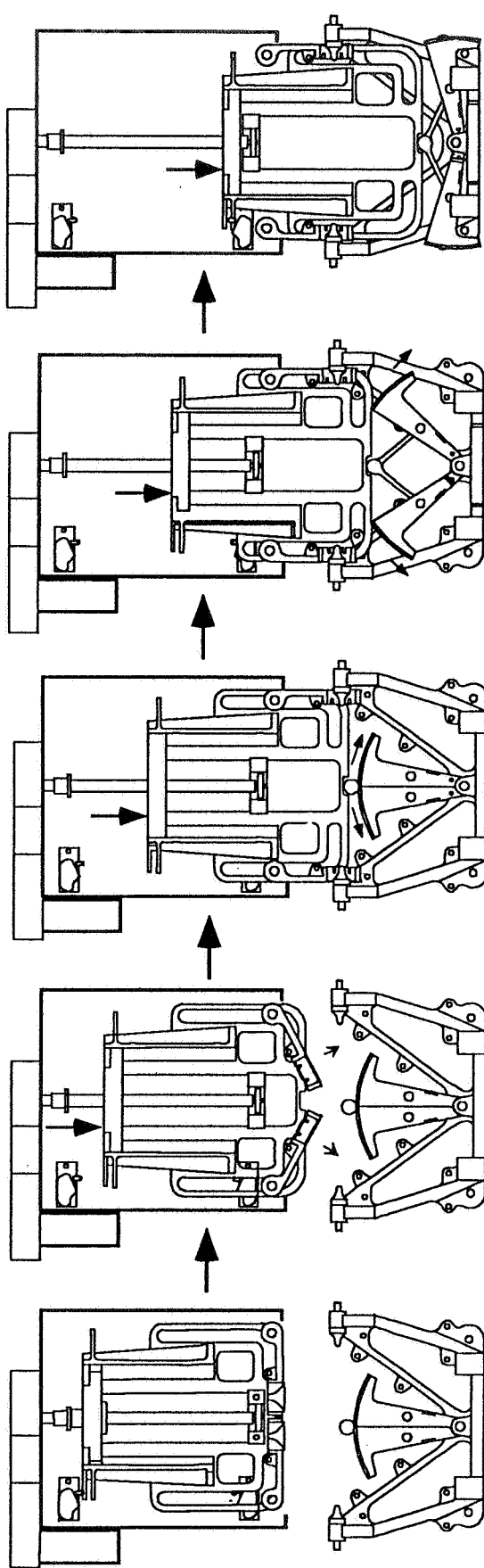
Fully Retracted, Coarsely Aligned
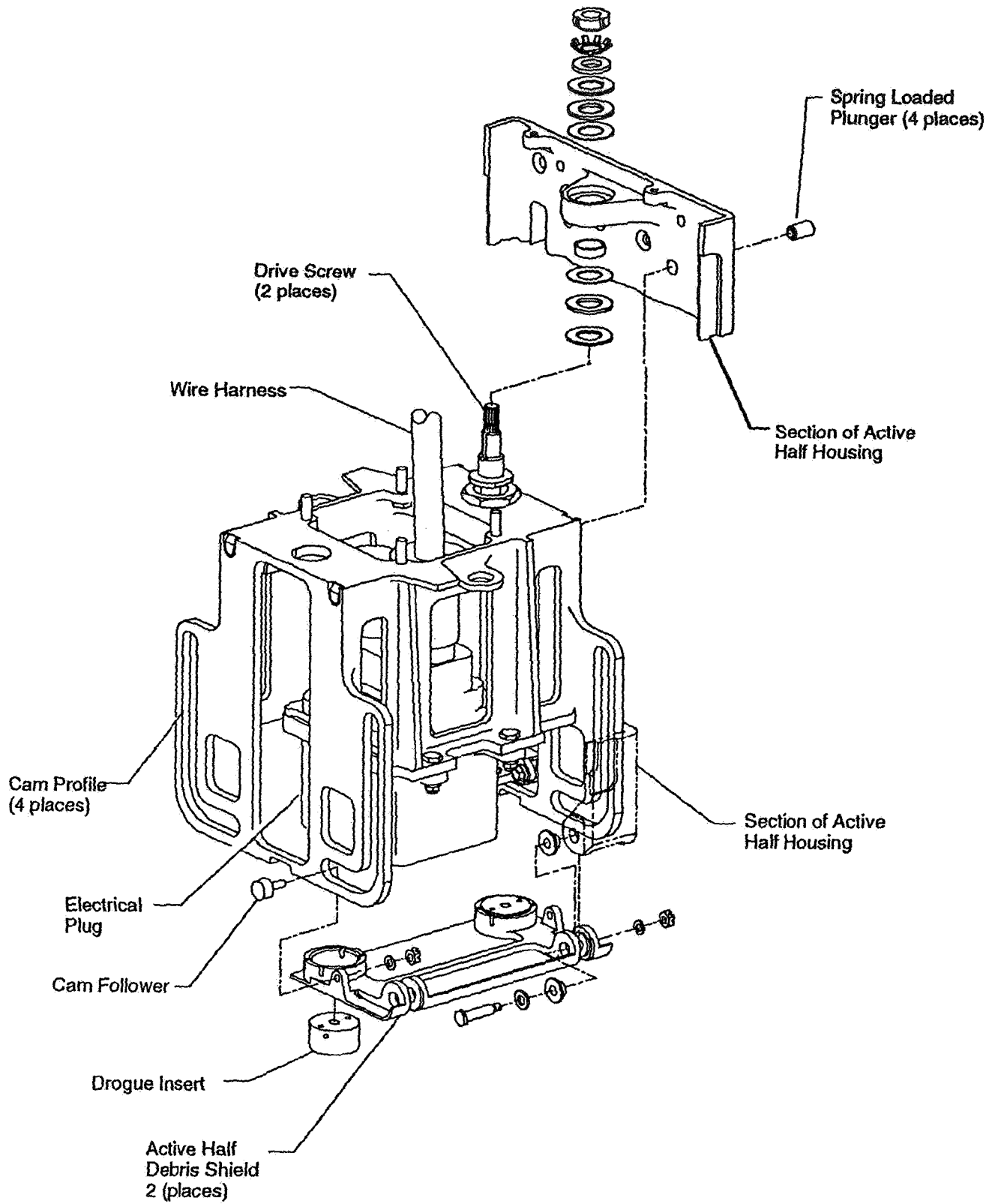
Carrier Begins To Move Down

Active and Passive Halves Aligned and Locked Together

Debris Shield on the Passive Half Begins to Open

Completely Mated Assembly

Note:
Electrical plug/receptacle and other details are not shown for clarity

Figure 5
Mating Sequence

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Spring Loaded
Plunger (4 places)

Drive Screw
(2 places)

Wire Harness

Section of Active
Half Housing

Cam Profile
(4 places)

Section of Active
Half Housing

Electrical
Plug

Cam Follower

Drogue Insert

Active Half
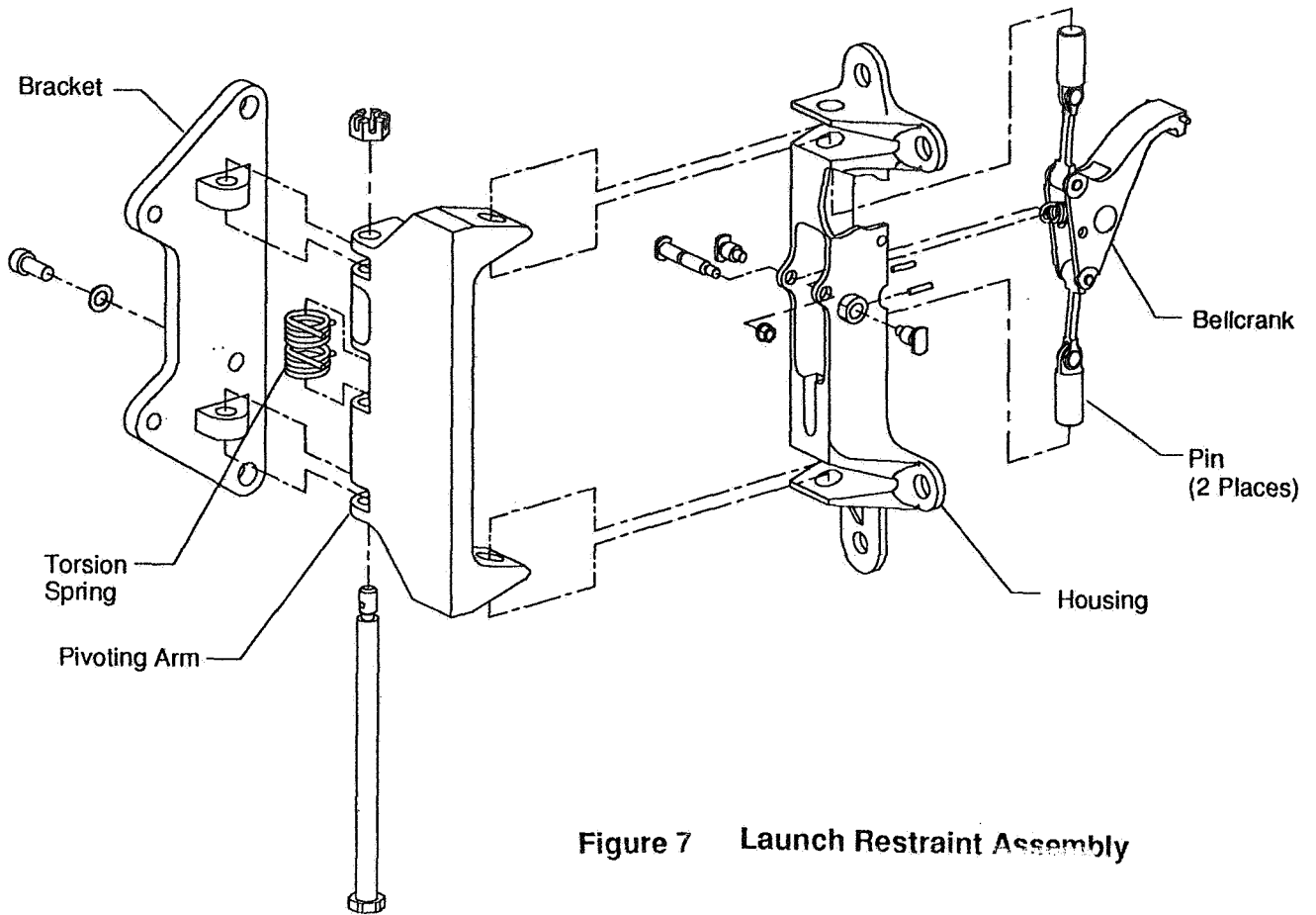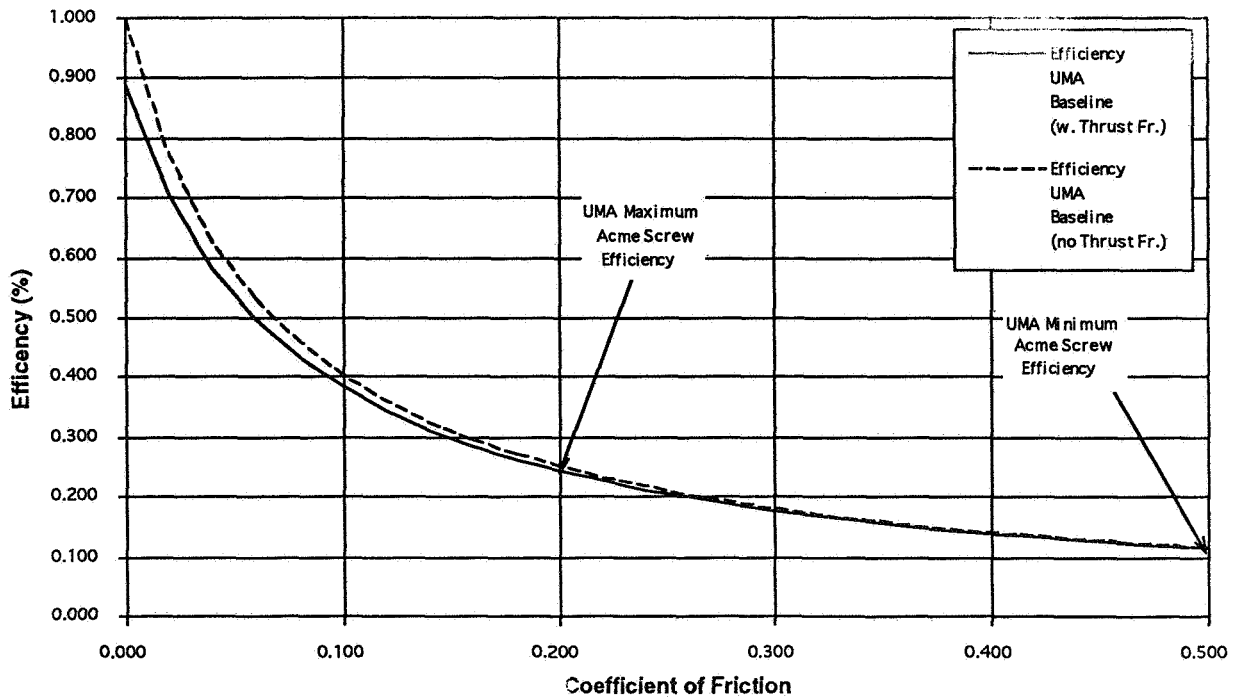Debris Shield
2 (places)

Figure 6
Carrier Assembly

Figure 7   Launch Restraint Assembly

Figure 8 UMA Drive Screw Efficency