The Micro Conical System: Lessons Learned from a Successful EVA/Robot-Compatible Mechanism

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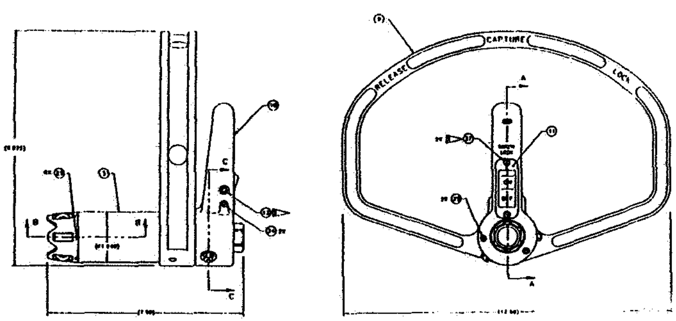
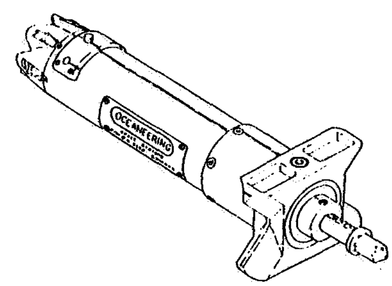
Abstract

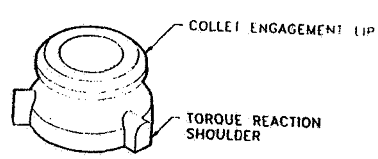
The Micro Conical System (MCS[1], Figure 1) is a three-part, multi-purpose mechanical interface system used for acquiring and manipulating masses on-orbit by either extra-vehicular activity (EVA) or telerobotic means. The three components of the system are the micro conical fitting (MCF), the EVA micro conical tool (EMCT), and the Robot Micro Conical Tool (RMCT). The MCS was developed and refined over a four-year period. This period culminated with the delivery of 358 Class I and Class II micro conical fittings for the International Space Station and with its first use in space to handle a 1272 kg (2800 lbm) Spartan satellite (11,000 times greater than the MCF mass) during an EVA aboard STS-63 in February, 1995. The micro conical system is the first successful EVA/robot-compatible mechanism to be demonstrated in the external environment aboard the U.S. Space Shuttle.



EVA Micro Conical Tool



Robot Micro Conical Tool



Micro Conical Fitting (1.47" Base Dia.)

Figure 1. Micro Conical System

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1 U.S. Patent No. 5,320,395

Introduction and Background

The International Space Station (ISS) will be maintained primarily through the exchange of new on-orbit replaceable units (ORUs) for expired ORUs. The micro conical fitting is designed to be the primary interface to grasp ORUs and to provide the local torque reaction needed for turning the heads of the ORU retention bolts. These bolt heads are typically located in the center of the MCF. The MCS is capable of handling ORUs up to 1272 kg (2800 lbm) and is rated for use on the ISS for ORUs up to 600 kg (1320 lbm). The micro conical fitting is an ISS standard interface.

The micro conical system was derived by combining the space station operational drivers with Oceaneering's unique experience in developing tools and interfaces for use underwater by telerobotic systems and commercial divers. Like many undersea structures, the space station will be maintained by both telerobotic work systems and direct human intervention (EVA crew).

The most successful approach to coaxing useful work from telerobotic systems underwater has been to use them primarily as tool delivery systems. This approach encourages the use of standard interfaces and of smart tools that have a front end common to both the human (diver or astronaut) and the telerobot. Importantly, this approach also allows tools to be adapted to the capabilities of the work system (human or telerobot), and the telerobotic systems to be designed to the simplicity level needed for reliable operations. Experience has shown that making a mechanical system simple enough for a telerobot to use will also improve its human compatibility.

The primary operational drivers for MCS development were the extreme volume and envelope requirements needed to accept the alternate space station standard tool and interface system. (The alternate system consists of the H-handle, micro interface, and the end-effector of the Special Purpose Dexterous Manipulator, or SPDM. The SPDM end-effector is called the ORU Tool Change Out Mechanism, or OTCM). Whereas the micro/OTCM combination requires an approach envelope of at least 35.5 cm (14 in) in diameter, the MCS approach envelope diameter is only 5.6 cm (2.2 in, Figure 2).

The micro conical system is unique in several ways:

1) From the outset, it was designed to be compatible with both EVA astronauts and space telerobotic systems. Testing and development were performed in parallel.

2) It is based on the lessons learned through twenty years of underwater work with both telerobots and commercial divers. These lessons drove a system that consists of a single interface and two tools: one for the astronaut, and one for the robot. However, the two tools have a common front end, which is used to grasp the fitting, and vary primarily in the means of actuation.

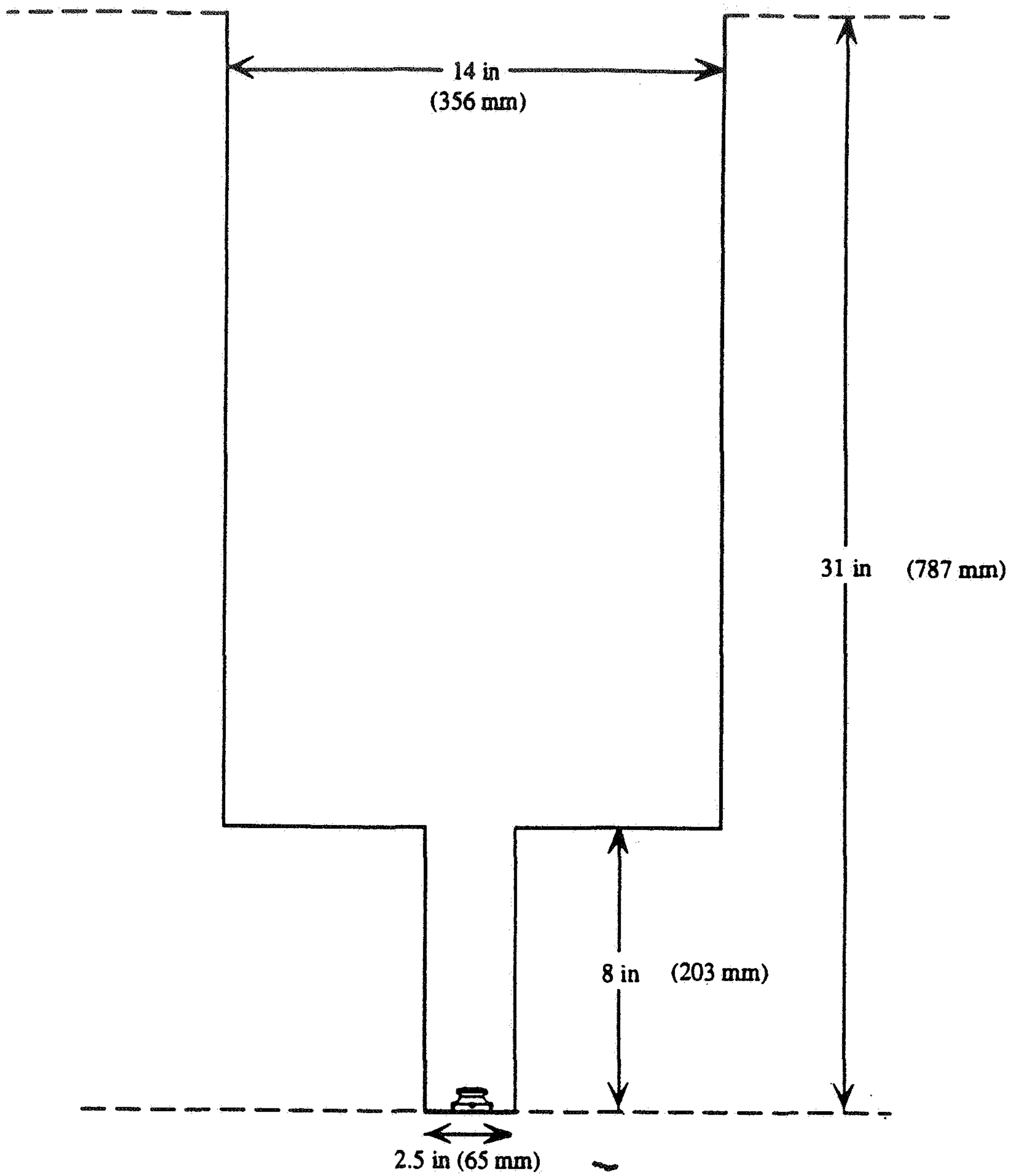

Figure 2. MCS Approach Envelope

3) The MCS is quite compact and lightweight: the fitting weighs only 0.11 kg (0.24 lbm), and the EVA tool weighs only 2.63 kg (5.8 lbm). Despite its size, the fitting is rated to ±227 kg (±500 lbf, shear and axial) and ±184 N-m (±250 ft-lbf, bending and torsion). The tool is rated to input loads of 76 N-m (167 ft-lbf) in torque and bending and 85 kg (187 lbf) in shear and axial loading (these numbers do not include safety factors used in the actual testing).

4) The MCS provides a high misalignment, latching soft dock. Thus, even when the tool is misaligned by up to ±7° with respect to the vertical axis, the collets will still latch to the lip of the fitting, hence providing a loose connection that can only be broken by deliberate motion of the collect actuator to the release position. In normal operations, the collets are moved from the soft dock position to hard dock or release either by an EVA actuator lever or by rotary input from the telerobotic system end-effector.

Micro Conical System Concept Development

From the start, the MCS was intended to be an integrated EVA/telerobot-compatible ORU handling system. It originally included an EVA tool, a robot tool, and two fittings: the conical and the micro conical. In the initial concept, the two powered tools featured a common front end and gear box/motor combination that could be grasped and used by either work system (EVA or telerobot). The tool, known as the multi-purpose torque tool (MPTT), could also interface with both the micro conical fitting and the larger conical fitting. From earlier design experience with underwater tools and interfaces, OSS understood that the fittings and tools had to be designed together.

The initial geometry of the micro conical fitting included a ramping lip, or groove, designed to accept detent pins. This feature evolved into the flat lip at the top of the final design. The MPTT design, therefore, included a set of three spring loaded pins that interfaced with the MCF at the ramping lip. The pins were designed to spring into the MCF geometry and provide a detent soft dock with the proper axial force. They were then locked into place by a spring-loaded locking ring.

Initial testing of the system took place in 1990-1991 in both the Johnson Space Center (JSC) Weightless Environment Training Facility (WETF) and the OSS Robotic Test and Integration Laboratory (RTAIL). RTAIL testing showed that teleoperators had difficulty in pinpointing the occurrence of soft dock. Telerobotic testing also showed that:

- the pin/groove geometry resulted in very high stress concentrations at the pin/groove interface, resulting in frequent MCF galling
- soft dock should be achievable from a highly misaligned position
- a latching soft dock would be preferred to a detent.

From testing the MPTT and related EVA/robot-compatible hardware in the WETF, astronauts also indicated a preference for a latching soft dock ("soft latch") over a spring detent. In a soft latch, spring-biased latches, or collets, on the tool engage a complementary geometry, or "lip," on the passive interface and "latch." In this condition, the two parts are mated but may still have some relative motion.

When the collets are moved firmly against the lip, pre-loaded, and then locked in place, the tool is considered "hard docked" to the interface and ready for further use (as a torque reaction point and/or for ORU handling).

In 1991, Space Station requirements drove OSS to abandon the conical fitting and MPTT and to concentrate on developing the micro conical system. The first EVA proof-of-concept micro conical tool (Figure 3) was completed in December, 1991, and tested extensively in the JSC WETF and in NASA's parabolic flight airplane, the KC-135.

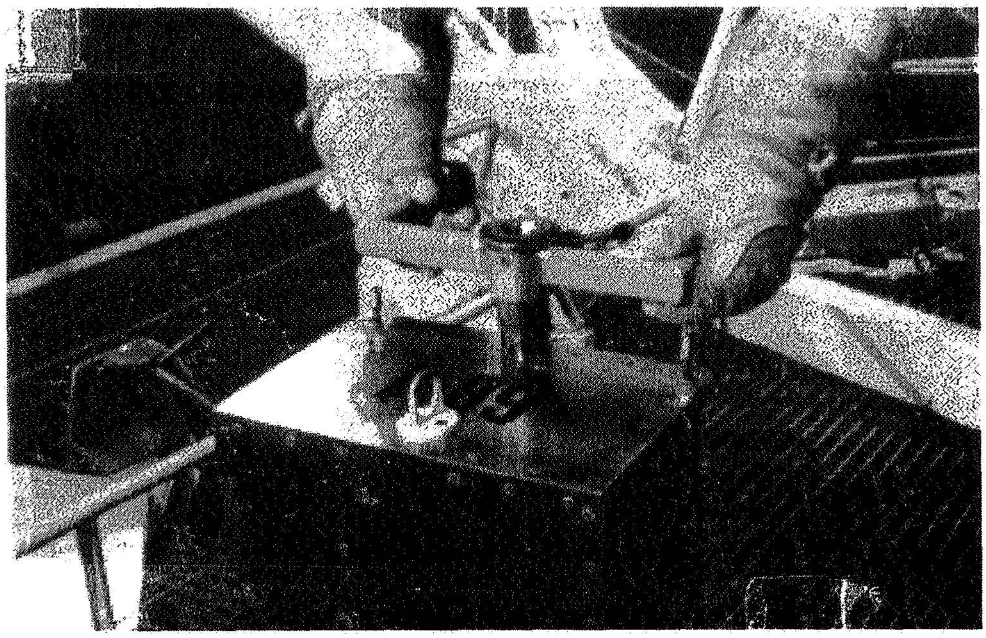

Figure 3. EVA Proof-of-Concept Micro conical Tool

This proof-of-concept tool and the re-designed MCF incorporated all of the geometric features and lessons learned, as described above. The six collets on the tool tip interfaced with the underside of the flat lip at the top of the MCF. The castellations on the end of the tool tip interfaced with the torque reaction pins located at 120° increments about the circumference of the MCF (these castellations also provided six discreet tool-to-fitting orientations).

In use, as the collets are pushed over the top of the MCF and past the edge of the lip, they move outward and then inward, providing both a soft latch and a visual status indicator to the user. As the handle at the rear of the tool is rotated clockwise, the internal collet carrier rides up a cam, thereby moving the collets upward and inward until they are seated firmly against the fitting. At this point, the user has established a rigid connection, or hard dock, between the fitting and tool.

Although this tool and fitting combination worked quite well, OSS identified several technical issues to be improved in the next generation:

- •The collets were too narrow and not strong enough to take the desired load range.
- •The separate status indicators incorporated into the collet geometry were unnecessary because they were redundant, and they needlessly raised the cost and compromised the structural integrity of the collets.
- •A single cam slot could not take the desired load, so an additional slot was added.

Based on the success of the first EMCT, OSS was directed by NASA to develop the first proof-of-concept RMCT. The design was reviewed and approved in June 1992. The resulting product (Figure 4) is still in use by the NASA Robotic Systems Evaluation Laboratory and is currently being used to test and verify robotic hardware for the ISS[2]. This design incorporated the lessons learned in the RTAIL and WETF and used the same internal mechanisms as the EMCT, but with collets of increased size and strength.

The actuation of the RMCT is necessarily different from the EMCT. Instead of the manual rotary actuator of the EMCT, the RMCT uses rotary input from the telerobot end-effector, the OTCM (Figure 5). The OTCM is expected to provide torque output incrementally up to 37 N-m (50 ft-lbf) in either direction. It can also extend and retract approximately 7 cm (2.78 in)[3]. The 7/16" hex head, located at the rear of the RMCT, drives one of two internal splines and is turned by the OTCM. In the driver-retracted position, the hex head interface drives the RMCT collets inward or outward. When the extend function is actuated, the OTCM torque driver pushes the hex interface outward, disengages one spline, engages another, and forces the RMCT torque driver to a position approximately flush with the tip of the tool. This second spline is part of the RMCT torque driver, so when torque is applied by the OTCM to the hex head in this position, the torque is passed directly to the RMCT torque driver, which can be used to engage or disengage an ORU retention bolt. Collet position status (release, soft latch ready, or hard dock) is provided by mechanical visual indicators located near the tool tip, within the field of view of some proposed OTCM cameras.

The RMCT/MCF interface was recently tested by NASA for its stiffness and misalignment characteristics. The results of those tests are as follows[4]:

	Load/Torque	Moment Arm	Test Load	Average Stiffness
Axial	454 kg (1000 lbf)	n/a	454 kg (1000 lbf)	95365 kg/cm (82,600 lbf/in)
Bending	34 N-m (550 in-lbf)	24 cm (9.45 in)	27 kg (60 lbf)	1634 N-m/rad (26,600 in-lbf/rad)
Torsion	55 N-m (900 in-lbf)	7.62 cm (3 in)	136 kg (300 lbf)	2820 N-m/rad (45,900 in-lbf/rad)

In each case, neither the MCF nor the RMCT yielded.

[2] Large 6B Avionics Box Orbital Replaceable Unit Robotic Compatibility Evaluation, Test Procedures, JSC-33331, October 1995 & Large 6B Avionics Box Orbital Replaceable Unit Robotic Compatibility Evaluation, Test Plan, JSC-33327

[3] ORU/Tool Changeout Mechanism Subsystem Specification, SPA- SS-SG-1027

[4] Robotic Track Task Robot Micro Conical Tool Characterization Test Report, JSC-33311, April, 1995

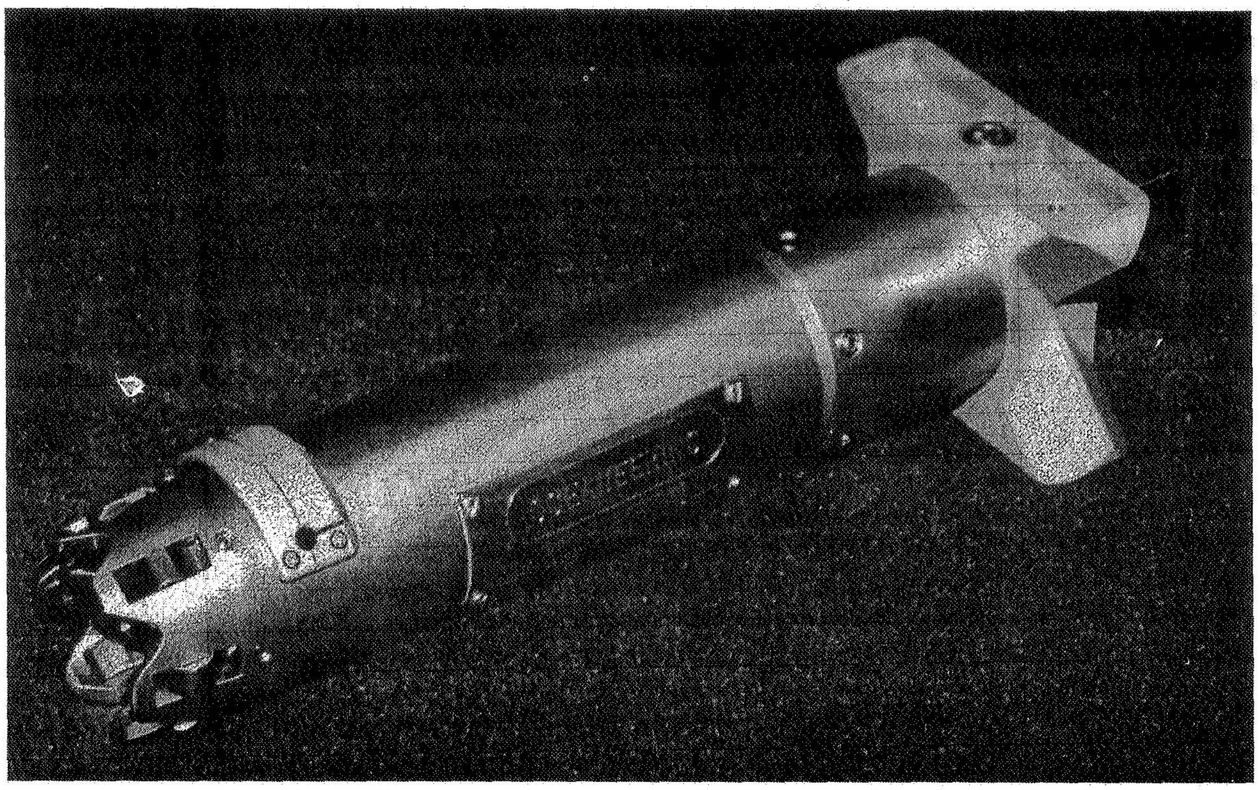

Figure 4. Proof-of-Concept RMCT

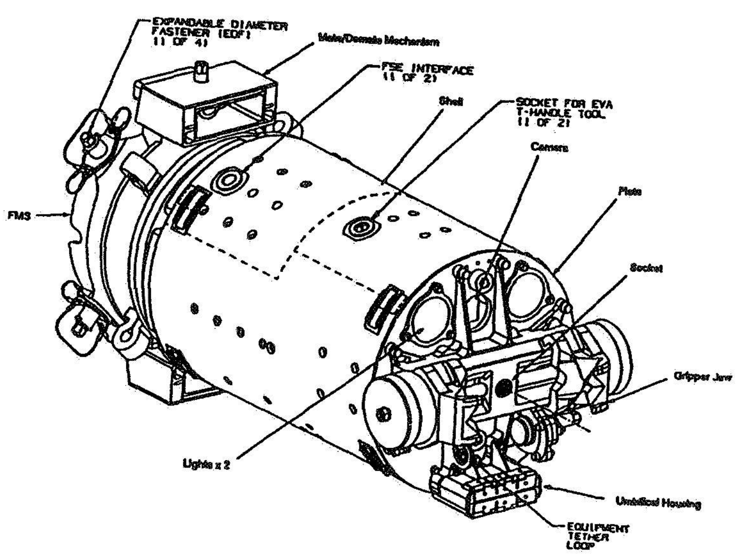

Figure 5. OTCM

The success of the RMCT design led the MCS design team to conclude that the larger collets should be incorporated into the next, and final, revision of the EMCT. The design team also questioned the use of press-fit pins, since the torque reaction shoulders for the MCF. The issues of assembly costs, reliability of the press fit in the thermal environment of space, and the ability of the design to react high torsional loads, led OSS to design the single-piece MCF that was ultimately flight-qualified.

In August, 1993, OSS signed a contract with McDonnell-Douglas Aerospace to complete development, flight certification, and manufacturing of the MCF and EMCT for ISS.

Micro Conical Fitting (MCF) Detailed Engineering

The MCF was designed as an EVA/robot-compatible handling interface for on-orbit manipulation of ORUs. As such, its design requirements encompassed limits of 227 kg (500 lbf) in axial and shear loading and 184 N-m (250 ft-lbf) in torsion and bending. In addition, the MCF has an operating temperature range of -93 to +82°C (-200° to +180°F) and an on-orbit lifetime of 30 years.

OSS designed three types of the MCF to satisfy all identified uses on the ISS: the 3/4" through hole, the counterbore, and the flanged fitting (Figure 6). All three configurations have an identical external geometry around the lip and torque reaction pin areas to allow grasping by either micro conical tool. The 3/4" through hole and counterbore MCFs are attached from their rear face using six 1/4-28" UNJF screws. The flanged MCF is attached using four No. 10 screws through the front flange face.

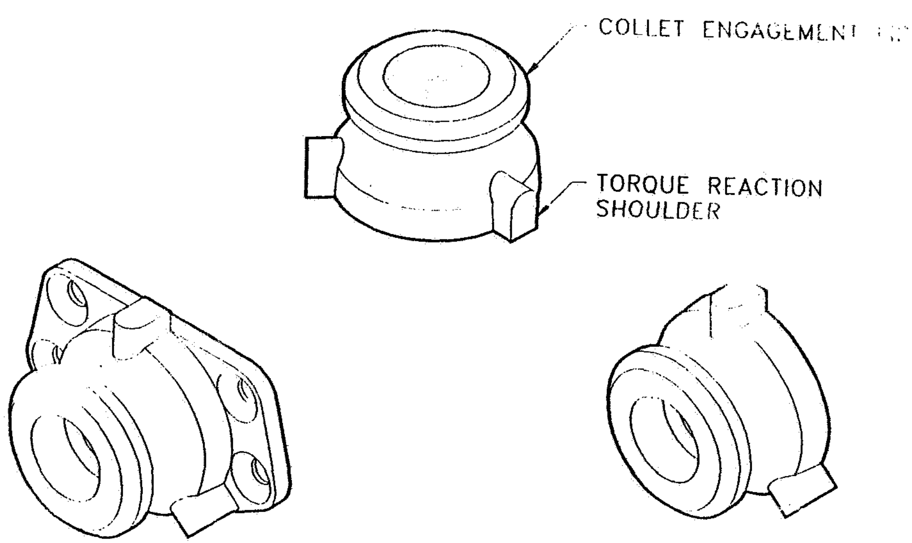

Figure 6. MCF Types

OSS performed preliminary analyses on the MCF to approximate the local stresses adjacent to the underside lip area and to determine the material properties required for the development test articles. Two development test articles were fabricated, one from CRES Custom 455 and one from MP35N.

OSS performed early development testing using an Instron machine to verify the results of the preliminary analyses. The development test units were subjected to the on-orbit loading forces of 184 N-m (250 ft-lbf) in torsion, 227 kg (550 lbf) in axial compression and tension, and a combined loading of 227 kg (550 lbf) in shear and 184 N-m (250 ft-lbf) in bending. Each test unit was instrumented with four rosette strain gauges positioned 90° apart on the inner surface of the through hole to allow for future correlation of stresses with the detailed FEA model. In order to simulate the loads applied by the micro conical tool tip, OSS fabricated a test jig that housed six beryllium copper collets, using preliminary material selected for the RMCT and EMCT collets. The MCF test units withstood all nominal loading conditions without any evidence of yield or failure.

During an unscheduled test when the MCF test units were subjected to a maximum of 6342 N-m (8600 ft-lbf), the collets of the tool test jig yielded. Although no yielding was observed at the MCF lip, there was substantial compressive plastic deformation from the tool tip on the upper surface of the torque reaction shoulders.

Fracture Analyses

The MCFs do not satisfy NASA ISS requirements for a non-fracture critical component. In particular, the momentum of a nominal ORU release from failure of a fitting would exceed the requirements of a non-hazardous released part during zero gravity flight. Additionally, the crew or robot limit load would induce maximum tensile stress in the flange or lip area of the part and exceed 30% of the ultimate strength of the MCF material (CRES Custom 455, condition H1000).

The fracture mechanics analyses were therefore tailored to verify that the configuration of the MCF in the lip area of the fracture critical zone had an adequate life expectancy. The standard crack sizes listed in SSP 30558[5] were assumed to be in the worst-case location and orientation on the part. Based on the worst-case stress distribution, conservative fatigue spectra were applied to verify part survival for a minimum of four service lifetimes.

An iterative process of fracture mechanics analyses and different types of non-destructive evaluations were performed to determine the proper sensitivity of inspection. Liquid penetrant inspection (per MIL-STD-6866, Type II, Sensitivity 3) was selected and implemented. Under these circumstances, electropolishing becomes a requirement and is used to remove smear or masking materials from mechanically disturbed surfaces induced by the fabrication processes.

[5] Fracture Control Requirements for Space Station

<u>Finite Element Analyses</u>
The finite element analysis examined the static strength and the structural non-linearity where the tool collets come into contact with the MCF lip. Figure 7 shows a coarsely meshed model resembling the development test article. The model was constructed from eight-node, hexahedral elements over the entire part. Even though the mesh size was fairly coarse, it was sufficient to verify that the area of greatest concern for stress was the re-entrant fillet radius of the collet engagement lip. After having identified the zone of highest stress, the model (Figure 8) was constructed. It has a very fine mesh in the lip area and extends to the bottom of the cylindrical portion adjacent to the conical part of the MCF body.

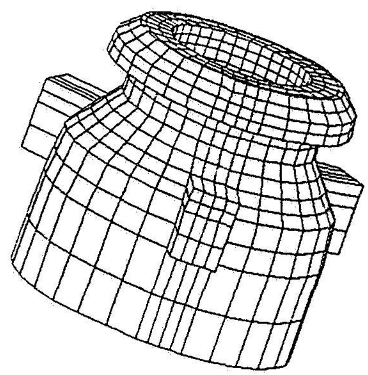

Figure 7. MCF Coarse Mesh Model

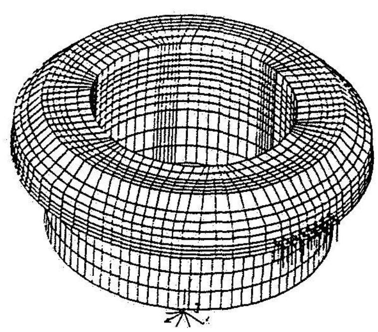

Figure 8. MCF Lip Fine Mesh Model

The model is fully constrained over the bottom cross-section of the cylinder. This model was used for all finite element stress calculations.

In order to determine the collet loads applied to the previous model, it was necessary to construct a spring model of the MCT with representative stiffness elements of the internal components. These loading conditions were then applied to the fine mesh model of the MCF lip area. To determine the margin of safety at the fillet radius of the lip, the calculated stresses were combined with factors of safety (1.10 on yield and 1.50 on ultimate), a 1.15 fitting factor, and a 0.95 reduction of material strength (due to operating temperature range). The minimum margin of safety was determined to be 0.269.

Only the enveloping crew-induced loads were considered during the analysis of the Space Station MCFs. Prior to the first use of the MCFs on STS-63 as a handling interface for the Spartan payload, OSS performed additional analyses unique to this mission. Identifying a remote possibility that the EMCT might not release from the MCF, OSS analyzed the vibrational loads that would be imparted to the MCF by the tool in case of re-entry with the tool still attached to the Spartan and in the payload bay. This analysis showed that re-entry loads were enveloped by the crew-induced loads.

EVA Micro Conical Tool (MCT) Detailed Engineering

The EVA micro conical tool interfaces with all three types of the MCF. The specification loads for the tool design were derived from the maximum crew-induced, on-orbit load of 85 kg (187 lbf) applied at any point on the tool. Like the MCF, the tool was designed for an operating temperature range of -93°C to +82°C (-200°F to +180°F), but with an on-orbit lifetime of only 10 years (due to a change in the International Space Station design life). The primary operational design requirements were the highly misaligned soft latch and the automatic spring back to capture-ready mode for the actuation lever.

Materials selection for the MCT addressed structural considerations under the applied limit loads, the potential for galling of the internal components during operation under load, and the possibility of cold welding of the MCT to the MCF under prolonged thermal cycling.

To determine the individual loads imparted by each tool collet to the MCF in the worst-case loading configuration, preliminary analysis on the MCT was performed using the spring model from the MCF finite element analysis. It was assumed that the areas of concern in the tool tip would be the collets and their pivot pins.

Two development tools were produced for testing in the WETF and aboard the KC-135 aircraft.

<u>EMCT Fracture and Loads Analysis</u>
The EMCT does not satisfy the requirements for non-fracture critical assemblies. Specifically, the EMCT is designed to function as a portable ORU handle, allowing the crew to manipulate large payloads without extra tethers. Due to the potential risk of a released mass during zero-gravity operations, this use of the EMCT results in an operational configuration where the tool becomes a Criticality I hazard. For each

piece part that is identified as fracture critical, the highest stress associated with each fracture-sensitive area was analyzed. Appropriate stress concentration factors were applied. Standard crack sizes for liquid penetrant NDE (identified in JSC 22267A) were used on the fracture-critical components. Conservative fatigue spectra, based on the worst-case stress distribution, were applied to each part for verification of part survival during four service lifetimes (a service lifetime consists of three missions that include up to four EVA uses followed by a contingency landing). All fracture-critical parts were inspected using liquid penetrant methods (per MIL-STD-6866, Type I, Sensitivity 3). Additionally, all fracture-critical parts were either electropolished (for CRES alloys) or etched (for aluminum alloys) to remove residual surface smearing prior to NDE inspections.

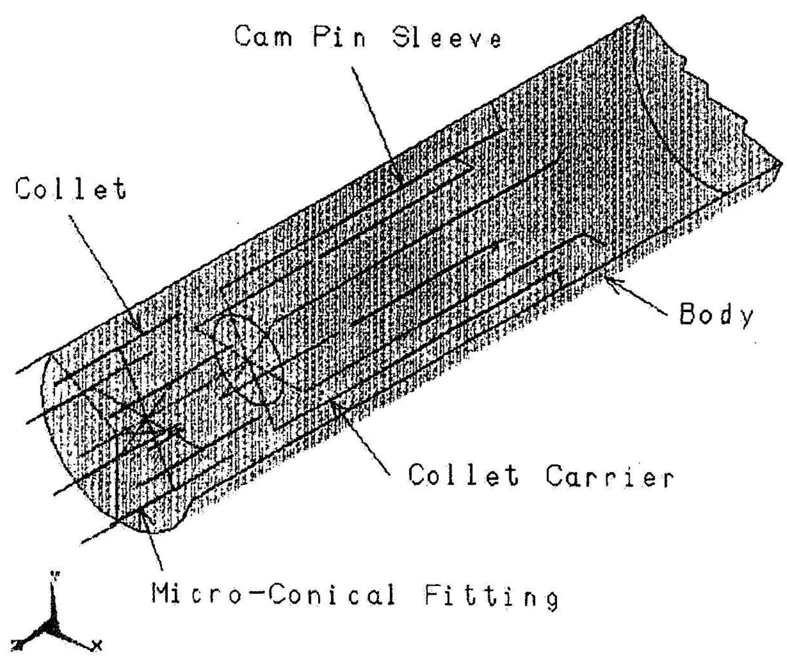

Figure 9. MCT Spring Model

The spring model of the MCT (Figure 9) was used to derive the worst-case stresses in each load-bearing component. The outer barrel of the MCT is represented by shell elements. Gap/contact elements were placed between the MCT collets and the MCF lip at six equidistant locations and between the MCT tool tip and MCF torque reaction shoulders at three equidistant locations. As the loading was applied to the model in various directions, some gap elements made contact while others opened up.

Because the mechanical elements in the load path were not accessible for instrumentation during testing, this approach was the only feasible way to determine the state of the surface contacts under the various loading conditions.

A total of 96 different external loading conditions were applied to the spring model to generate individual component stresses. To determine the margin of safety at the fillet radius of the lip, the calculated stresses were combined with factors of safety (1.10 on yield and 1.50 on ultimate), a 1.15 fitting factor, and a 0.95 reduction of material strength (due to operating temperature range).

The Failure Modes & Effects analysis performed on the STS-63 EMCT identified only one critical failure where the EMCT could not be released from the MCF even after engaging the contingency release mechanism. To disposition this potential failure, structural analysis was performed on both the EMCT and MCF to prove that a failed tool could withstand the vibrational loads encountered during re-entry.

The MCT (Figure 10) was successfully used on STS-63 to manipulate the Spartan payload. This was the first on-orbit demonstration of the EMCT and MCF. It proved that a carefully designed mechanical system with an interface mass of only .11 kg could be used to handle satellites as much as 11000 times the interface mass (the Spartan satellite weighed 1270 kg).

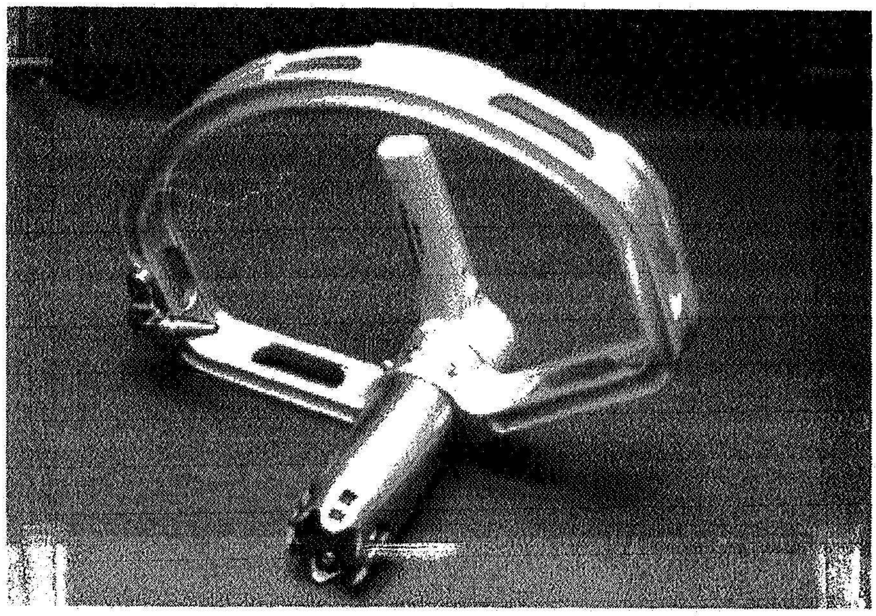

Figure 10. STS-63 MCT
Micro Conical System Certification

Micro Conical Fitting(MCF) Certification
The 3/4" through hole and counterbore MCF designs were certified for space flight at NASA JSC. Certification was accomplished by test for the loading configurations and life cycle and by inspection for the workmanship and mass properties.

The loads tests were conducted at the NASA ES Structures Test Laboratory and used limits loads of 227 kg (550 lbf) and 184 N-m (250 ft-lbf). A fitting factor was applied to all limit loads. Factors of safety of 1.1 were applied for yield loads, and 1.5 were applied for ultimate loads. In order to test for the environmental requirements of -93°C to +82°C (-200°F to +180°F), the applied loads were increased by an additional 6% to account for the reduced load-carrying capacity of Custom 455 stainless steel at +82°C (+180°F, MIL-HBK-5[6]).

As required in the Specification Control Document governing the certification requirements for the MCF, the loads were applied in the following order for each load condition: limit load, yield load, ultimate load. The load conditions were:

- axial tension
- axial compression
- torsion
- bending with simultaneous shear.

After static testing was completed, a cyclic test was performed to verify the 6000-cycle service life. A test jig, consisting of a functional tool tip, was used to grapple the MCF and then hard dock. These functions were controlled by hydraulic actuators that drove the tool tip onto the MCF to the soft dock state, hard docked the tool tip, released the collets, and withdrew the tool tip away from the MCF.

Micro Conical Tool (MCT) Certification
The STS-63 version of the EMCT was certified for space flight in March, 1995. As with the MCF, load tests were conducted at the NASA ES Structures Test Laboratory. Applied to three positions along the EMCT handle, load tests were performed at only 1.1 times the limit load of 85 kg (187 lbf). All installation and actuation forces, including contingency release, were verified to be within their specification for temperatures ranges of -93°C to +82°C (-200°F to +250°F). Life cycle testing was limited to 200 cycles for certification on this specific mission.

Conclusions

The success of the micro conical system as an EVA/robot-compatible mechanism can be attributed to the basic approach of the design team. In particular, the team understood that:

- the basic design must be driven primarily by operational considerations
- a mechanism designed for one work system, then modified for the other, will please neither; therefore, development must be as an integrated system
- EVA and telerobot operations testing should be conducted in parallel
- the lessons learned from the testing must be used

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[6] Metallic Material and Elements for Aerospace Vehicles Structures

- a very small, axisymmetric fitting with appropriate load paths and compatible tooling is capable of handling satellites or other masses as much as 11,000 times the mass of the fitting
- a latching soft dock is a useful capability for both astronauts and telerobots
- a common EVA/robot interface and front-end-of-tool-design, with differing crew and robot actuation and handling interfaces, is as viable an approach to on-orbit tools as it is to underwater tools
- human/robot-compatible tools and interfaces will become an enabling approach to space exploration and work.

Designing a mechanical system for <u>both</u> EVA and robotic compatibility need not increase the size, cost, or complexity of the "basic" system. Furthermore, as long as human compatibility requirements and capabilities are considered from the outset, designing a tool and interface system to the limited capabilities of a telerobot can actually enhance the human compatibility of the system: "if the robot can do it, it should be easy for the astronaut."

If a mechanism is made for human use, operations are the key. After the basic operations and configuration have been determined through iterative testing, then the detailed design can take place. The micro conical system proves that mechanisms can be equally compatible with humans and telerobots, and that operational constraints can be used to create reliable, simple, and strong mechanical systems.