A NOVEL PASSIVE ROBOTIC TOOL INTERFACE

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ABSTRACT

The increased capability of space robotics has seen their uses increase from simple sample gathering and mechanical adjuncts to humans, to sophisticated multi-purpose investigative and maintenance tools that substitute for humans for many external space tasks. As with all space missions, reducing mass and system complexity is critical. A key component of robotic systems mass and complexity is the number of motors and actuators needed. MDA has developed a passive tool interface that, like a household power drill, permits a single tool actuator to be interfaced with many Tool Tips without requiring additional actuators to manage the changing and storage of these tools. MDA's Multifunction Tool interface permits a wide range of Tool Tips to be designed to a single interface that can be pre-qualified to torque and strength limits such that additional Tool Tips can be added to a mission's "tool kit" simply and quickly.

1. Background

The increased capability of modern space robotics has seen their potential uses increase from simple sample gathering and mechanical adjuncts to manned EVAs, to sophisticated multi-purpose investigative tools and replacements for human astronauts on many external maintenance space tasks. As with all space missions, mass is of critical importance and a key component of robotic systems mass is the number of motors and actuators needed to perform the tasks assigned to the robotics. There is also a continuing need to reduce space mission complexity, potential failure modes and mission verification costs.

Acknowledging this drive to reducing mass, complexity and cost, MDA has developed a novel passive interface that, much like a common, household power drill, permits a single tool actuator to be interfaced with a multitude of Tool Tips without requiring additional actuators to manage the changing and storage of these Tool Tips. The underlying concept behind the Multifunction Tool Interface is to use the existing actuators required to enable the robotic manipulator that will use the tools to perform the additional functions needed to change the Tool Tips. The interface uses the arm actuators to perform the actions needed to mate and demate the Tool Tips instead of using additional actuators to perform those functions. The result is a lightweight and extremely strong interface that has significant flexibility and excess capability to handle unplanned and contingency operations.

MDA's Multifunction Tool was developed for the Next Generation Canadarm (NGC) program, funded by the Canadian Space Agency, with the aim of creating a series of ground testbeds to develop and evaluate various on-orbit robotic servicing technologies. As part of this program, the Multifunction Tool Interface permits a wide range of both simple and complex Tool Tips to be designed to a single interface that can be pre-qualified to torque and strength limits. This also allows third party tool suppliers to add tools to a mission's "tool kit" simply and quickly as mission requirements evolve.

Once on orbit, the design of the tool interface permits Tool Tips to be picked up and dropped off simply by use of the robotic manipulator arm that holds the tool actuator. No other actuators are required. In addition, the interface provides significant load carrying capacity and permits torque from the tool actuator to be passed through to the Tool Tip to perform any of the functions that the tool designer requires. Lastly, articulation of the tool actuator permits the Tool Tip to be indexed within the interface to provide an additional degree of freedom allowing the Tool Tips to be optimally positioned for both planned and unplanned tasks during a mission.

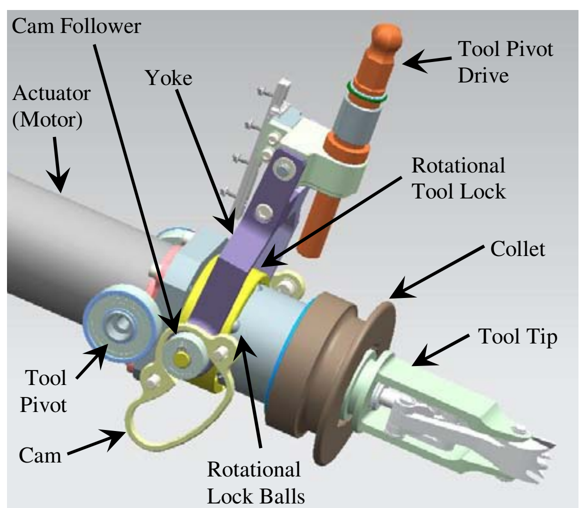

Figure 1 Multifunction Tool Components

The Multifunction Tool was designed and built for the NGC Program and has undergone testing as part of that program that has revealed the concept's strengths as

'15th European Space Mechanisms & Tribology Symposium – ESMATS 2013'
Noordwijk, The Netherlands, 25–27 September 2013

well as several details that need attention prior to use in a flight program. Since the conclusion of the NGC Program, the MFT has been used as a development tool for other space robotics programs.

2. Tool Interface Description

As noted above, the key concept that enables Tool and Tool Tip mass reductions is to use the robotic arm to perform additional tasks that mate and demate the smaller Tool Tips from the single actuator motor that provides the mechanical power to these Tool Tips. This does require that the arm motors be sized to accommodate a significantly increased number of motor cycles and can increase the size and mass of the arm motors, however, trade studies undertaken during the NGC program showed that if any more than three different powered tools were required for a mission, the increased mass of the motors when using the MFT Interface was more than offset by the reduced number of motorised tools being carried compared to a single motorised tool with replaceable Tool Tips.

Programmatically, the use of the replaceable Tool Tips with a common interface also permits the development of new tools tips late in the program development cycle in response to unexpected issues that may occur. The interface can be prequalified with significant excess capacity and then additional Tool Tips developed and added to the mission with no further qualification or integration testing required. It is hard to overstate the benefits such flexibility can bring to on-orbit robotic task and mission planning.

The heart of the Multifunction Tool (MFT) interface consists of the following two subassemblies shown in Fig. 1, the Collet Mechanism and the Tool Tip. Additional degrees of freedom are added by incorporating the Tool Pivot Drive, a Tool Pivot, the Rotational Tool Lock, Cam and Cam Follower, also shown in Figure ***1*** 1, but this is a supplementary capability.

The core interface capabilities are provided by the design of the Collet and the Tool Tip. The interface mechanism works similarly to that of a quick disconnect mechanism. Ball bearings slide into slots in the tool to lock it axially. The balls fit into depressions in the Tool Tip which restrict the Tool Tip body from rotating within the Collet. Simply sliding the collet back and forth performs the locking and unlocking action.

Fig. 2 shows the elements common to all Tool Tips that enable the passive interface mechanism. The Retention Dimples engage with the locking balls within the Collet to retain the Tool Tip axially and to prevent the Tool Tip from rotating. The Drive Shaft rotates and is connected to any Tool Tip elements that require actuation. The Tool Tip can therefore also include a gearbox to modify the applied torque or speed. The Drive Spline engages a ball drive that is part of the Tool Actuator to supply the torque to the Drive Shaft. Lastly, the Retention Collar engages with the Tool Tip Retainer Lip on the Berthing Holster (Fig.5) to help retain the Tool Tip in the Holster. The Collar also helps guide the Tool Tip through the mate/demate procedure ensuring that the Tool Tips can be passively attached and detached from the robotic arm.

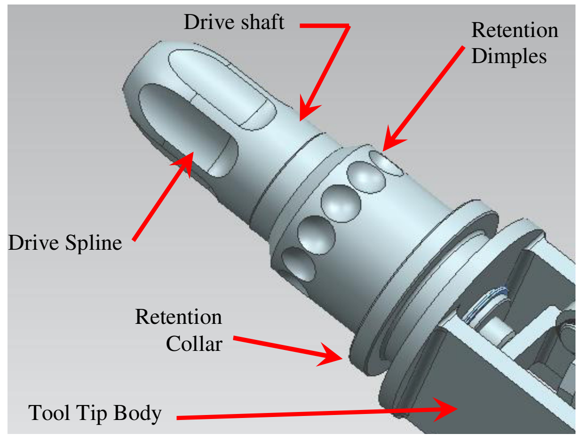

Figure 2 Tool Tip - Interface Elements

Fig. 3 illustrates the Tool Tip in the unlocked position. The Collet is pushed back away from the Tool Tip compressing the Collet Springs. This allows the six ball bearings to engage six of the eighteen dimples arranged circumferentially around the shank of the Tool Tip. The excess number of dimples permit the tool rotational angle to be varied (in this case in 20° increments) prior to locking the tool in place. This provides an additional degree of freedom that can be used to allow the tool to adapt to unplanned situations on orbit.

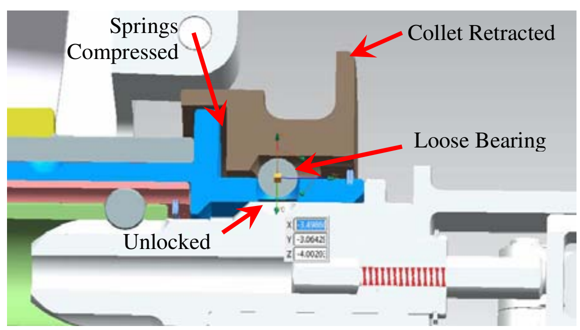

Figure 3 Tool Tip Collet – Unlocked

On the NGC tool, the Tool Tip is rotated via another mechanism, explained below, powered by the tool actuator but other methods of engaging the Tool Tip in the differing index positions can be readily imagined.

Fig. 4 shows the Tool Tip Collet in the locked position.

The Collet has been pushed forwards, towards the Tool Tip, by the Collet Springs pushing the ball bearings radially inwards. The bearings are now constrained between the bearing collar and the dimples in the Tool Tip, locking the assembly together.

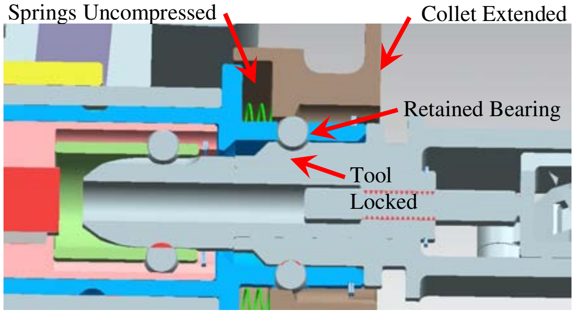

Figure 4 Tool Tip Collet - Locked

Tool Tips are the replaceable working elements of the design and can be designed to be completely static or to take advantage of torque provided by the single actuator attached to the tool body that can provide torque through the centre of the collet mechanism to the Tool Tip. The Tool Tip shown in Fig. 1 is designed to cut and hold fine wires. The cutter jaws are opened and closed by the rotation of the actuator motor. A wide range of simple and compound acting tools can be designed to take advantage of the actuator's torque and the standardised MFT Interface.

As mentioned above, the mass reductions expected from the Multifunction Tool concept derive primarily from using the existing robotic manipulator motors to actuate a passive mechanism that can manage a multitude of replaceable Tool Tips. The key to this passive tool management system is the collet and how it interacts with the Tool Tip Berthing Holster. The working faces of the Berthing Holster are shown in Fig. 5.

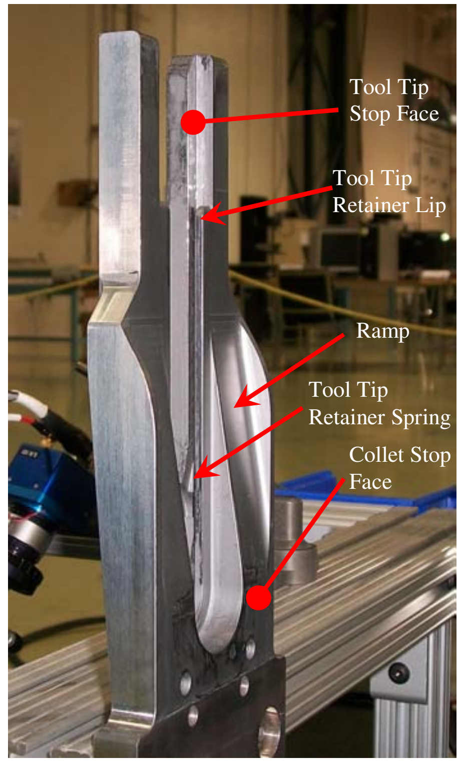

Figure 5 Berthing Holster Details

Fig. 6 illustrates the Tool Tip demating sequence. To demate a Tool Tip from the Multifunction Tool the robotic manipulator manoeuvers the MFT into position in front of the Berthing Holster. The MFT is advances so that the Retention Collar on the Tool Tip rests against the Tool Tip Stop Face on the Berthing Holster (Fig. 6A). While maintaining a contact force between the Retention Collar and the Tool Tip Stop Face the manipulator arm then translates the Tool Tip until the Retention Collar is captured by the Tool Tip Retention Lip (Fig. 6B) which then serves to guide the rest of the process. As the manipulator continues to translate the Tool Tip deeper into the Holster, the face of the Collet

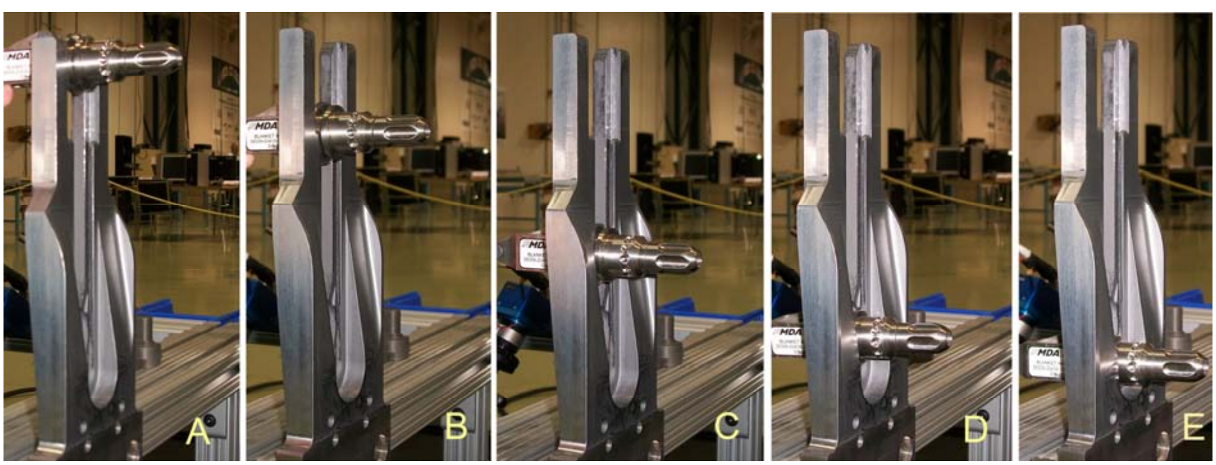

Figure 6 Tool Tip Demate Sequence

contacts the Ramp on the Holster (Fig. 6C) which, as the Tool Tip is translated, forces the Collet out of engagement. By the time Tool Tip the reaches the end of the Ramp (Fig. 6D), the Collet has been completely retracted and the Tool Tip is free of the MFT. To retain the Tool Tip within the Holster, the manipulator continues to translate the Tool Tip until is passes the Tool Tip Retainer Spring and bottoms out within the Holster (Fig. 6E). The MFT can then be withdrawn and the Tool Tip is both demated and secured within the Holster.

To mate a new Tool Tip the above process is reversed. The MFT is manoeuvred until the end of the Tool Tip enters the Collet opening and then the MFT is advanced until the face of the Collet contacts the Collet Stop Face on the Holster. At that point the manipulator must continue to apply axial force so that the Collet can be retracted and become unlocked so it is ready to accept the new Tool Tip. Once the Collet is fully retracted, the manipulator translates the Tool Tip out of the Holster. The manipulator must continue to apply force to the Collet to keep it compressed over the entire length of the Ramp. By the time the Tool Tip and MFT have been manoeuvred to the end of the Ramp (Fig. 6C) the Tool Tip has engaged with the Collet and the balls have locket the Tip in place. The mated MFT is then translated out of the Holster ready for use.

Ensuring that the Collet is kept retracted as the manipulator translates the MFT down the ramp generally requires the use of Force Moment Sensing (FMS) in the manipulator to ensure the correct forces are being applied, but FMS is also generally required in such manipulators in order to perform the robotic mission tasks, so this is not an additional requirement due only because of the MFT Interface.

3. Additional Tool Capabilities

As mentioned above, for the NGC program MDA incorporated additional capabilities into the MFT and the Collet mechanism to better perform the desired tasks. The manipulator arm that holds the MFT also holds other tools and performs other servicing functions during the design reference mission. The MFT, therefore, is itself a removable tool, one of several that are designed to fit onto the end of the NGC manipulator arm. The mechanism the picks up and holds the tools also has a rotating torque drive so it was decided to use that drive to provide additional functionality for the MFT. The first function is that with the Tool Tip secured within the MFT Collet, the Tool Tip may be rotated around its long axis and locked in one of 18 positions, providing a 20° indexing capability. The second function is that the angle of the MFT actuator can be modified over a range of approximately 40° during operations. These serve to dramatically increase operational flexibility without incurring the complexity of additional motors and controllers.

Achieving the additional capability involves tilting the tool actuator axis and then linking that motion to the Rotational Tool Lock that locks a ball drive to the Tool Tip Drive Spline grooves. Referring again to Fig.1 and to Fig 7, the Tool Pivot Drive engages the torque drive on the manipulator arm. Rotating this Pivot Drive, via a lead screw, a linear bearing and the Yoke, forces the Cam Follower to follow the Cam which provides a compound motion. The first action is to move the Rotational Tool Lock forward until grooves in the Lock engage the Rotational Lock Balls in the Collet assembly. Until the Rotational Tool Lock engages the balls, activating the actuator will rotate the Tool Tip within the MFT.

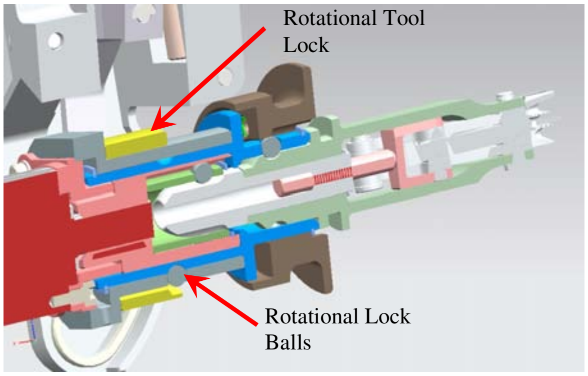

Figure 7 Tool Tip Rotation Lock Mechanism

Continuing to rotate the Pivot Drive pushes the Cam Follower further around the Cam and causes the Actuator and Collet axis to rotate in pitch relative to the Pivot Drive axis. With the Tool Tip now locked in position, rotational motion provided by the actuator rotates the Tool Tip Drive Shaft, and not the whole Tool Tip, thus actuating the Tool Tip function.

4. Testing and Lessons Learned

Testing the MFT Interface concepts occurred at several levels. The first testing used a rapid-prototyped breadboard to evaluate the basic mechanism and metal prototypes to evaluate the strength of the tool drive components.

Fig. 8 shows the ball spline prototype that was used to evaluate the rotational and axial capabilities of the numerous ball splines and lock that are part of the MFT Interface concept. Testing the components to 600% of maximum predicted torque resulted in some brinelling where the balls contacted the grooves of the ball spline, but no indications of either failure or binding of the locking collet. Obviously, there is significant excess capacity in the design which could result in further mass reductions if the design was optimised, however the decision was taken to retain the design as is because the whole tool was already significantly under its mass target.

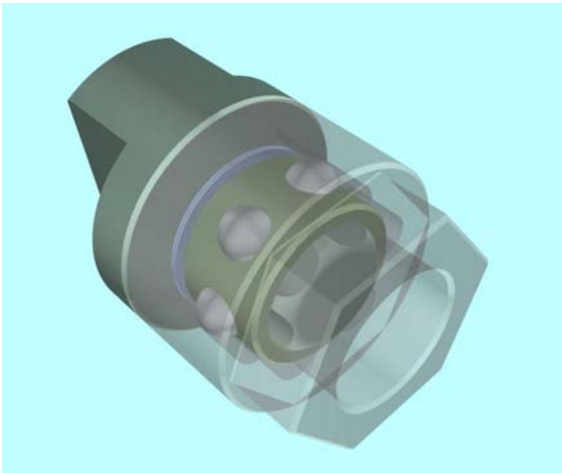

Figure 8 Ball Spline Breadboard

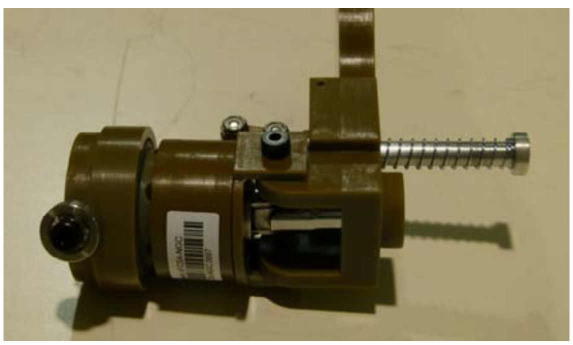

Figure 9 Initial Collet Mechanism Prototype

As frequently occurs, the initial breadboard testing showed up several problems that were overcome as the design evolved. The first collet prototype (Fig. 9) used a linkage to tilt the Tool Tip, but this was found to provide insufficient range of motion before a singularity was reached and the mechanism became unstable. Fig. 10 represents the second and final collet mechanism concept and was used to evaluate the initial Berthing Holster concept which is shown in Fig. 11.

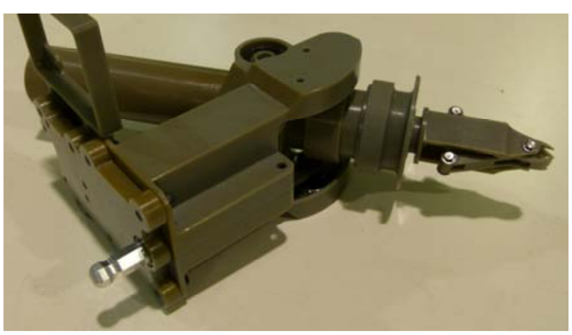

Figure 10 Second Collet Mechanism Prototype

Figure 11 First Berthing Holster Prototype

The first Berthing Holster design relied upon flat spring sections to provide compliance for Collet retraction and the retention of the released Tool Tips. However, testing showed that while a human operator could make the Collet mechanism reliably release and engage the breadboard Tool Tip when hand held, the precise control of the forces and actions were beyond the capabilities of the manipulator being designed as part of the program.

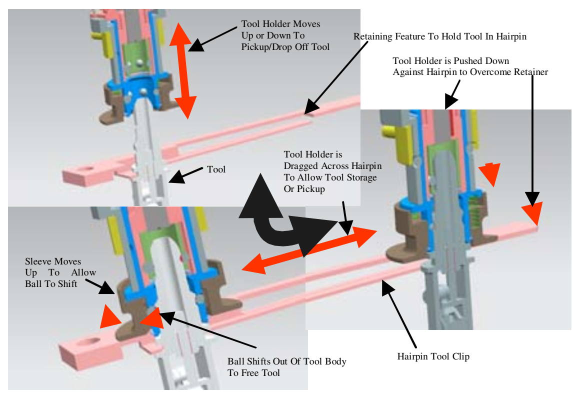

Figure 12 Initial Berthing Holster Operation

The second and final design of Berthing Holster, as shown in Fig. 13, imposes significantly fewer operational requirements on the manipulator system. Testing of the final Holster design with the completed testbed MFT and Tool Tips showed that the overall concept was sound but revealed a problem that would have to be addressed for a flight program. The amount of play between the Retention Collar of the Tool Tip and the slot in the Berthing Holster combined with the relatively small amount of engagement of the Retention Collar in the slot caused binding when the Tool Tips were being mated to the MFT. This was exacerbated by the amount of play between the Cam and Cam Follower on the MFT. The Cam play would allow the Actuator and Collet assembly to nod freely in pitch approximately 3-4° and the engagement of the Retention Collar was insufficient to retain the alignment needed for smooth movement. When the Actuator and Collet assembly was held rigid, the Tool Tip could be extracted easily and the mating sequence occurred smoothly.

Figure 13 Second Berthing Holster Prototype

Demating the Tool Tips from the MFT using the current tool and Berthing Holster designs went very smoothly as the forces were being generated and resolved within the Collet/Berthing Holster system and the Tool Tip did not bind.

Figure 14 NGC Manipulator Testing MFT Interface

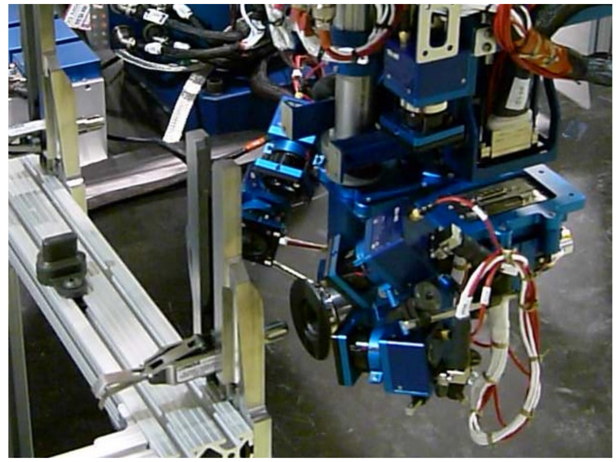

Figure 15 MFT Approaching Tool Tip

5. Conclusions

The Multifunction Tool Interface concept provides a significant mass-reduction benefit to those missions where multiple robotic tools are required and where mission parameters benefit from a flexible approach to providing tools to perform multiple robotic operations for planned and contingency operations. The NGC Multifunction Tool testbed has shown that that the concepts are sound and revealed issues which are easily solved for a flight program thus successfully reducing program risks.