# An automated tether management system for microgravity extravehicular activities

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# An Automated Tether Management System for Microgravity Extravehicular Activities

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## Abstract

An automated tether system has been developed for the purpose of improving the efficiency of micro-gravity activities of fully suited astronauts. System features include gripping of multiple anchor types, remote release of the tether from an anchor, and controlled retraction of the tether. Two main mechanisms make up the system. First, a remotely releasable, self-locking robotic gripper with opposing jaws that grasps a variety of anchors such as handrails, tether loops, and guide wires. Second, an automated tether retractor that is capable of active or passive operation. Passive retractor operation saves power by emulating existing safety tether systems and active operation expedites tether retraction and allows towing.

## 1 Introduction

When working in the micro-gravity environment of space, ExtraVehicular Activity (EVA) operations rely heavily on the use of tethers to ensure that crewmembers and equipment remain in proximity of the spacecraft. An appreciable amount of time is spent managing these tethers.

Traditional tethers, such as the short waist tether [1], consist of a flexible tensile structural member with manually operated hooks at each end. These hooks are fastened around tether loops or cables that are integral to the equipment, suits, and structures with which the crewmembers interact. To allow greater freedom of motion, the retractable safety tether [1] is applied. This device features a spring-loaded reel that dispenses and controls the length of tether in the workspace. In the case of Space Shuttle missions, the safety tether also engages slide wires to allow greater freedom of motion.

When complete, the International Space Station will be the largest spacecraft ever constructed, requiring many tether loops, slide wires, and handrails to allow tethered travel about its exterior. In order to travel any appreciable distance along this structure, an EVA crewmember will need to transfer safety tethers between anchors, requiring them to attach to a new anchor, return to the initial anchor to release the first hook, and then continue their traverse. Since the velocity of crewmembers during EVA is deliberately slow, such transfers can be time consuming.

The purpose of the present research is to improve the mobility of EVA crewmembers in micro-gravity operations. An automated tether management system would simplify tether transfer by allowing a crewmember to remotely open a tether hook and retract the tether. This will be especially useful in areas of space structures where guide wires may not be present or convenient, particularly during construction of these structures. Additional potential applications for the automated tether management system include crewmember locomotion and object retrieval.

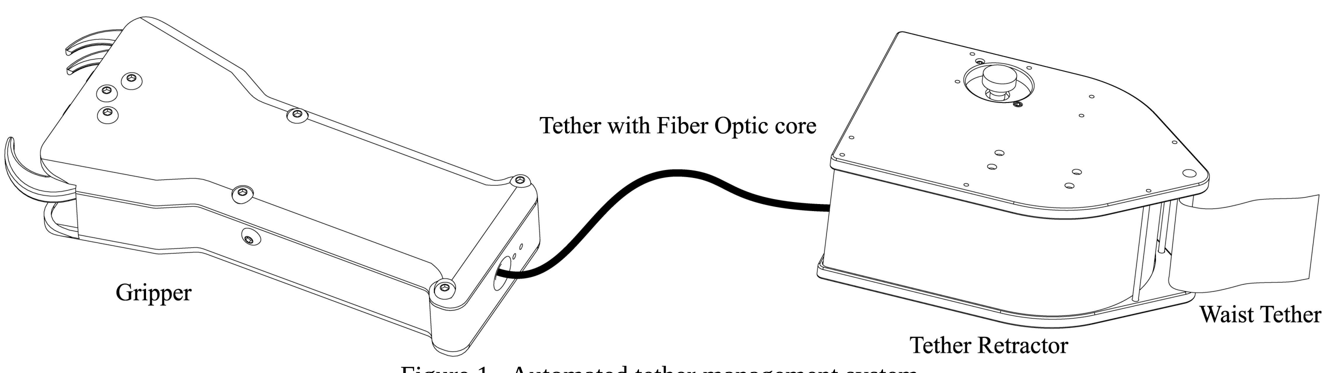



Figure 1. Automated tether management system.

The key components of the proposed automated tether system (Figure 1) are a remotely controlled robotic gripper, a power assisted tether retractor, and a hybrid tether that carries communication signals. The gripper positively engages an anchor by encirclement, locks without relying on system power, and is capable of remote disengagement. The retractor emulates existing passive tether retractors and adds the capability of active tether retraction. The retractor applies a force to the extended tether until the tether and gripper reach a terminal velocity, then saves power by disengaging the drive mechanism and allowing passive retraction. This allows continued tether retraction without consuming power or developing slack. The hybrid tether essentially consists of a Vectran [2] structural weave encasing a single-mode fiber optic core, which transmits commands from a manual interface on the retractor to the gripper.

## 2 Background and Requirements

Most design specifications were established by referencing NASA documents [1, 3, 4] that specify requirements for EVA tool performance. Additional requirements were also set in order to provide functionality that equals or surpasses that of existing flight hardware. Although independently derived, many of the gripper requirements coincide with those set by Mahalingam et al. [5] for gripping in space.

<u>Gripper Specifications</u>

Trade-offs between functionality and size were necessary to yield a suitable gripper design. Multiple degree of freedom (DOF) grippers provide superb functionality and adaptability, e.g. Biagiotti et al. [6], but also require considerable space for packaging actuators and sensors. Passive gripper designs, such as that of Arisumi & Komoriya [7] require minimal packaging but allow minimal control. The gripper of the present system was required to be an automated, stand-alone unit packaged within a reasonably sized handle, so the solution was to allow a maximum of one DOF while incorporating as many passive features as viable.

The following requirements were established for the automated gripper in order to meet and exceed the performance of existing tether hooks.

1. <u>Anchor Points</u>: The gripper will engage multiple anchors including standard EVA handrails and loops designed for existing tether hooks. This requires the gripper to pass through a loop with a 0.75-in minimum inner diameter and thickness of up to 0.5 in.
2. <u>Gripping</u>: The gripping mechanism will positively engage the anchor with either a loose or firm grip, and will lock redundantly. Maximum clamping force will be less than 25 lb to avoid damage to the anchor.
3. <u>Loading</u>: A 400 lb axial load, which includes a safety factor, will be supported.
4. <u>Release</u>: The gripper will not release unintentionally. It will allow active remote release as well as manual contingency release. During release, there will be minimal force exerted on the anchor by the gripper, keeping the free-floating gripper relatively stationary until it is retracted.
5. <u>Ergonomics</u>: Manual operation will require less than 30 in-lb of torque. The handle of the gripper will have minimum length of 3.75 inches and incorporate a non-slip, non-abrading surface.
6. <u>Power Supply</u>: Power will be supplied by an internal battery pack, which will be replaceable by a suited crewmember. The device will be able to be operated continually for 6 hours between recharges.
7. <u>Degrees of freedom</u>: The gripper will have one DOF to reduce complexity, save space, and minimize weight.

<u>Retractor Specifications</u>

The following requirements have been established based on existing retractable safety tethers as well as additional features desired of the system.

1. <u>Loading</u>: The retractor will bring a 550 lb mass at 4 ft per second to a stop with mass attenuation of less than 100 lb. The minimum design load will be 200 lb.
2. <u>Tether Length</u>: The retractor will contain a tether length of at least 55 feet in order to provide functionality similar to existing safety tethers.
3. <u>Retraction</u>: Retraction will be passive unless a driving force is required. Passive operation will be similar to existing retractable tethers, which require 0.5 pounds to extend the spring-loaded tether and incorporate a friction brake to prevent retraction. A 1.5-pound tether force overrides the brake. The driving force will automatically engage and disengage the tether reel as required. The maximum retraction rate will be less than 0.5 feet per second.
4. <u>Power Supply</u>: Power supply requirements are the same as those required of the gripper.

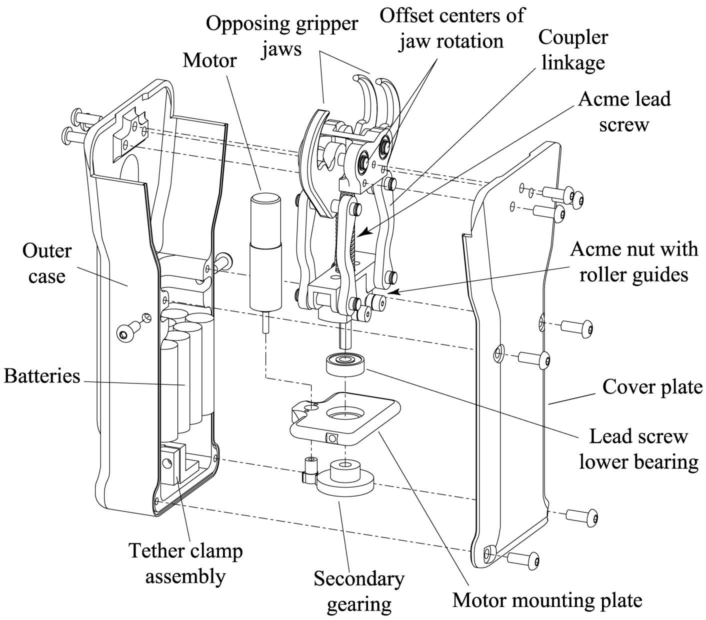


Figure 3. Gripper exploded view.

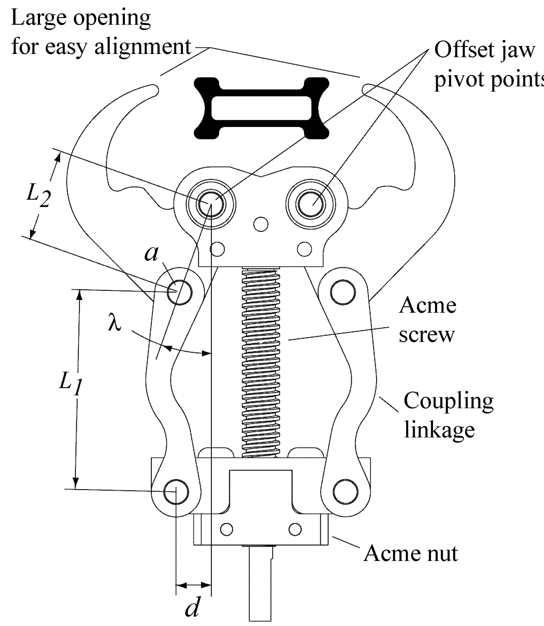


Figure 4. Gripper linkage.

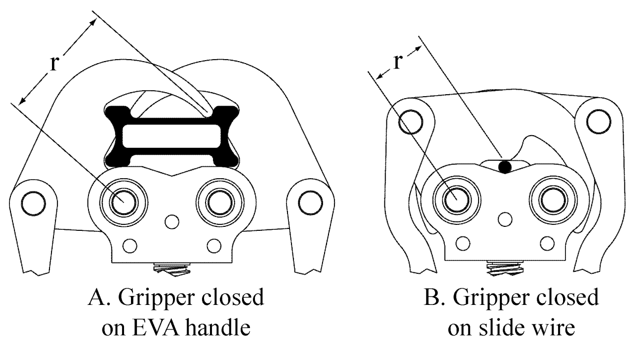


Figure 2. Range of gripper applications. The variable effective moment arm, r, is shown.

# 3 Prototype System

Gripper Prototype

An assembled view of the prototype gripper is shown in Figure 1, with an exploded view shown in Figure 3. The housing serves as a handle for the gripper and provides support to the jaws and tether. A geared motor coupled to a lead screw drives the three opposing jaws via the linkage shown. The housing also contains batteries for powering the system and all control electronics. Commands for opening and closing the gripper are received via a fiber optic core at the center of the tether or via tactile switches (not shown) on the handle of the gripper.

A configuration of opposing offset rotating jaws was chosen to maintain a single DOF while allowing the jaws to grip objects with large variations in size and shape. It also allows the gripper to open widely in a small space and reduces alignment problems when approaching the gripped object (Figure 4). When closed, the offset jaws intermesh and surround the gripped object in order to achieve positive engagement. The jaws can grip either loosely or firmly by partially or fully closing the jaws, respectively. Inner jaw geometry was chosen such that the gripper would firmly engage a variety of anchors including the relatively large EVA handrail and small 0.125-in diameter slide wire (Figure 2), as well as standard tether loops. Jaw actuation is accomplished by parallel four-bar linkages driven by an acme lead screw (Figure 3 and Figure 4). This linkage configuration was chosen for its capability to provide relatively constant gripping force on various-sized anchors if properly optimized, as described below. Rotation of the acme lead screw causes linear displacement of the acme nut, which in turn causes the coupler links to move and the jaws to rotate. The acme screw is self-locking, allowing the jaws to maintain position without applied power. The gripper thus locks passively and is designed to withstand forces at the jaws in excess of 400 pounds.

The linkage configuration was optimized to obtain a maximum yet uniform force magnification factor for a variety of anchors while limiting the required travel of the lead screw. This force magnification factor, $X_{Fmag}$, is defined as the ratio of the maximum force exerted by the jaws on an anchor to the linear force exerted by the acme nut, or using terms defined in Figure 4 and Figure 5,

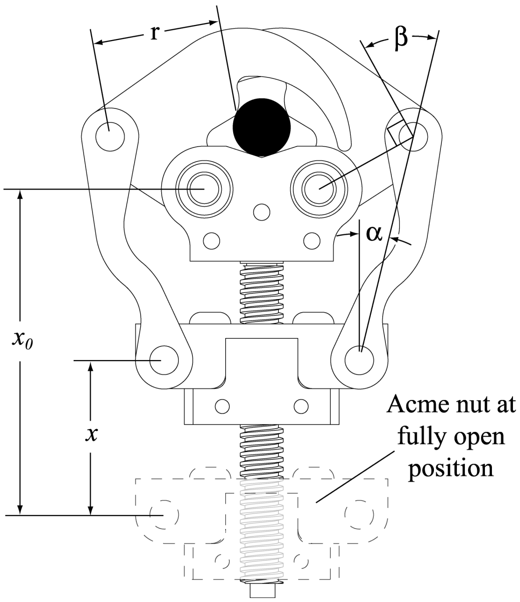



Figure 5. Parameters that determine grip properties.

$$X_{Fmag} = \frac{F_{jaw}}{F_{nut}} = \frac{T_{jaw}/r}{F_{nut}} = \frac{L_2}{r}\cos a \,\cos b \tag{1}$$

where

$$a = \tan\left(\frac{x_0 - x}{d}\right) - \sin^{-1}\left(\frac{L_1{}^2 + (x_0 - x)^2 + d^2 - L_2{}^2}{2L_1\sqrt{(x_0 - x)^2 + d^2}}\right) \tag{2}$$

and

$$b = \sin^{-1}\left(\frac{L_1{}^2 + L_2{}^2 - (x_0 - x)^2 - d^2}{2L_1L_2}\right) \tag{3}$$

The challenge, as Figure 2 indicates, is that the moment arm of the jaws acting on large objects, such as the EVA handrail, is larger than the moment arm acting on small objects, such as the slide cable. In order to avoid crushing some anchors and loosely gripping others when maximum force is applied, the linkage was optimized using constrained gradient-based techniques [8] to find the optimal configuration for gripping several different sized objects. As shown in Figure 4, the parameters varied during the optimization included the horizontal separation, $d$, between the jaw pivot and acme nut pivot, the length $L_1$ of the coupler link, the length $L_2$ between the jaw pivot and connection to the coupler link, and the initial angle $l$ describing the fully open position of jaw pin $a$ relative to vertical. A composite cost function formed by the 2-norm of the force magnification factors for four different anchors and the maximum nut travel distance, $D$, were used in the optimization:

$$F = \left\| f_1{}^2 + f_2{}^2 + f_3{}^2 + f_4{}^2 + D^2 \right\| \tag{4}$$

where

$$f_i = 2 - \left(X_{Fmag}\right)_i$$

The anchors included in the optimization were the EVA handrail, a 0.75-inch diameter round, a 0.50-inch round, and a 0.125-inch round. For geometric and packaging purposes, the parameters were constrained such that

$$0 \le l \le p \text{ radians}$$

$$0.1 \le L_1 \le 2 \text{ inches}$$

$$0.94 \le L_2 \le 2 \text{ inches}$$

$$-0.5 \le d \le 0.35 \text{ inches}$$

Starting the optimization from multiple initial configurations reliably indicated that the optimum configuration was described by

$$l = 0.31 \text{ rad} \quad L_1 = 2.0" \quad L_2 = 0.94" \quad d = 0.35"$$

which results in a maximum nut travel of 1.74 inches and a value of 2.9 inches for $x_0$ (Figure5). Resulting gripping properties for several anchors are summarized in Table 1.

Actuation of the gripper is accomplished with a 2.3-watt MicroMo 1528-012BRE brushless DC servo motor with integrated drive electronics, which is identical to the motor used in the retractor. The motor is fitted with a 14:1 planetary gearbox (MicroMo 16/7), and drives the 0.375-in, 12-thread-per-inch, single-lead acme screw through a 3.75:1 secondary gear stage. Maximum gripping force is approximately 23 pounds on the 0.5-in round, and maximum closing time is approximately 4 seconds on the 0.125-in round. The self-locking gripper is designed to support axial loads in excess of 400 pounds.

Table 1. Gripping characteristics for various anchors showing maximum force and effective grip moment arm.

| **Anchor** | **Moment Arm, r (in)** | **Nut Disp. *x* (in)** | **Max Grip Force (lb)** | $X_{Fmag}$ |
|---|---|---|---|---|
| EVA Handrail | 1.27 | 0.98 | 16.9 | 0.676 |
| 0.75" round | 1.19 | 1.26 | 15.8 | 0.632 |
| 0.5" round | 0.725 | 1.43 | 22.6 | 0.905 |
| 0.5" square | 0.728 | 1.47 | 21.6 | 0.865 |
| 0.25" round | 0.685 | 1.62 | 18.7 | 0.747 |
| 0.125" round | 0.642 | 1.73 | 15.3 | 0.614 |

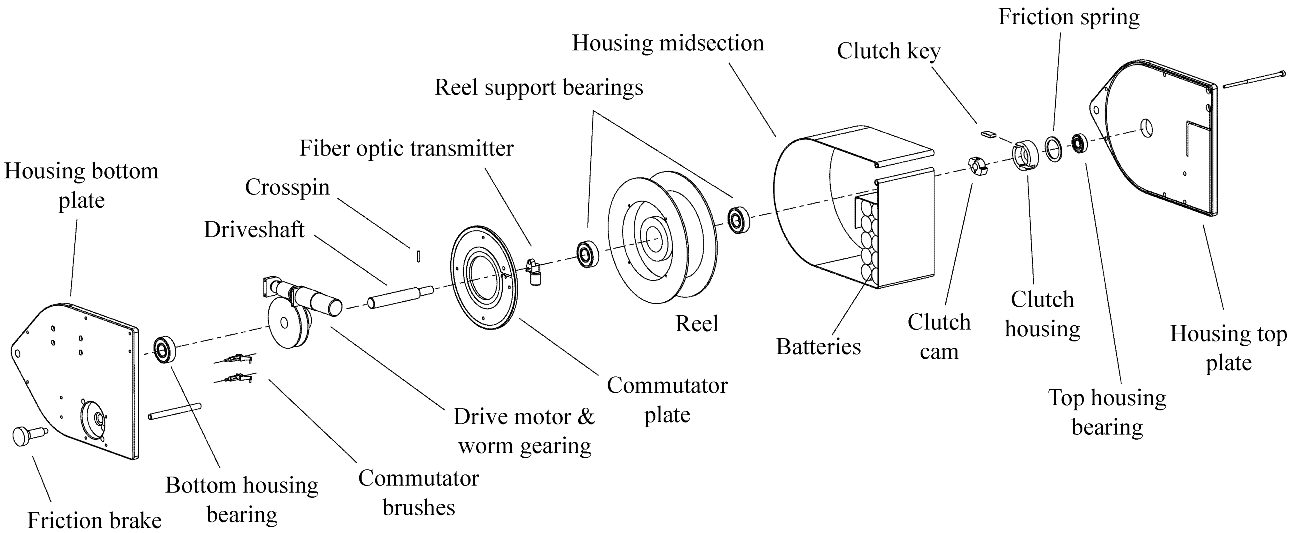



Figure 6. Exploded view of retractor.

Retractor Prototype

An exploded view of the automated tether retractor is shown in Figure 6. The primary components of the retractor are the housing, tether reel, and drive system. The housing consists of a bottom plate, an upper plate, and a midsection.

The housing bottom plate supports the drive motor, friction brake, commutator brushes, and a press-fit bearing. A similar bearing is contained within the top housing plate and together these bearings support and allow rotation of the drive shaft. The worm gearing and drive motor propel the drive shaft, which is coupled to the clutch cam. Unless the motor is activated, the shaft remains stationary, the clutch does not engage, and the reel is permitted to rotate bi-directionally relative to the drive shaft via the reel support bearings.

Spring retraction and a friction brake provide the retractor with passive behavior, which is designed to be identical to existing retractable safety tethers A spiral spring, not shown in the figure, provides a relatively constant tether retraction force of approximately 0.5 pounds. Retraction can be prevented by applying a brake, which consists of a spring-loaded friction pad that rubs on the side of the reel. Similar to the retractable tether currently in use, extension of the tether is still possible once the brake is applied, but a sufficient tether force, adjustable between 0.5 and 2.0 pounds, must overcome the friction. Batteries and control electronics are also contained within the unit.

The drive motor, worm gearing, and clutch mechanism provide active functionality to the retractor. The worm wheel is rigidly coupled to the drive shaft and the geared motor rotates the worm. The drive shaft passes through the reel bearings and is coupled to the clutch cam on the opposite side of the reel.

Activation of the drive motor engages the active drive system. The clutch housing, shown in greater detail in Figure 7, envelops the clutch cam and provides retaining slots to support the clutch keys. When the drive shaft rotates, the clutch cam turns relative to the clutch housing, and the thrust surfaces of the cam forces the clutch keys to contact the reel as shown in Figure 8B. If the keyways are misaligned, as shown in Figure 8C, the clutch housing rotates with the clutch cam until the keyways are aligned with the clutch keys. Once orientated, the clutch keys fully engage the keyways in the reel as shown in Figure 8D, which allows the motor to drive the reel.

The drive system disengages when the motor is deactivated or the spring-loaded reel turns faster than the terminal speed of the motor. This causes the clutch cam

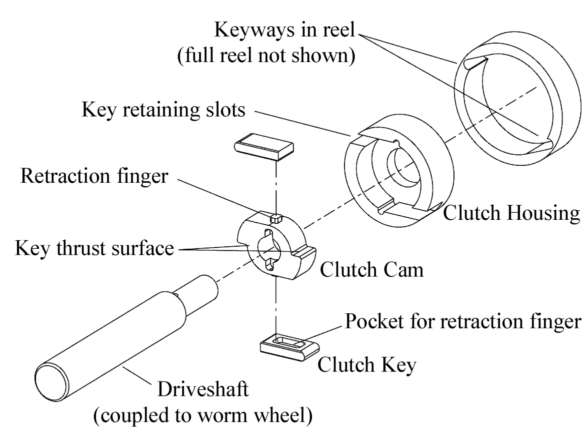
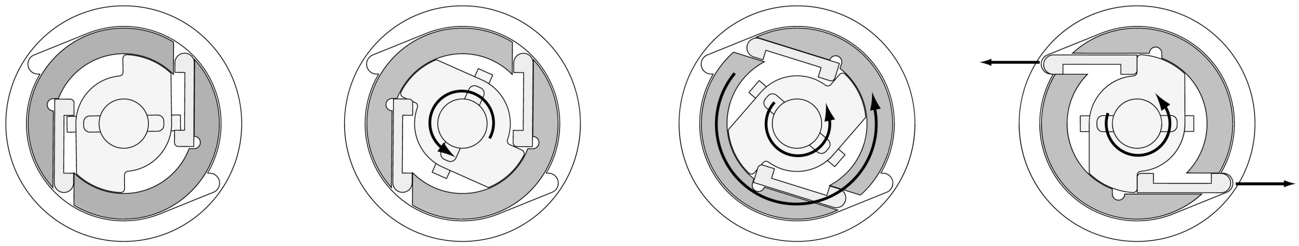



Figure 7. Exploded view of clutch components.



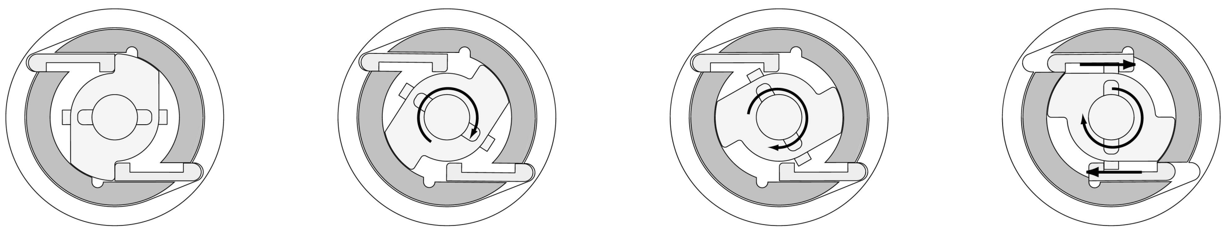
A. Keys initially retracted.

B. Crank cam rotates and engages keys.

C. Keyway misalignment results in housing rotation.

D. Housing aligns with keyways and keys drive reel.

Figure 8. Clutch engagement process.



A. Clutch initially engaged.

B. Crank rotation reversed.

C. Fingers engage pockets on keys.

D. Fingers disengage keys and reel may rotate passively.

Figure 9. Motor reversal clutch disengagement.

to rotate relative to the clutch housing until the fingers engage the key pockets, Figure 9C. The clutch cam continues to rotate until the keys are completely disengaged, Figure 9D, and the reel is allowed to rotate independent of the motor. The spring-loaded reel can then passively retract the tether, preventing excess tether from accumulating in the workspace while ceasing to consume power.

The motor used in the retractor is identical to that of the gripper, including the gear transmission ratio of 14:1. Together with a single-lead worm stage with 40:1 reduction, the system can apply a nominal tether retraction force of 3.8 pounds with a terminal velocity of 0.4 ft/sec. If used as a means of locomotion, this would be sufficient to accelerate a fully suited astronaut to the terminal velocity within 10 seconds.

<u>Multifunctional Tether and Communications</u>

Commands are transmitted from the retractor to the gripper via a single-mode plastic fiber optic element at the core of the tether. This mode of communication was selected because of challenges in the operating environment: radio communication is not practical due to available frequencies, infrared transmissions are affected by extreme variations in light levels and blockage of line-of-sight, and long conductors traveling at high velocities through Earth's magnetic field can produce voltages that may damage motors and electronics. Braided Vectran structural strands surround the fiber optic element and provide a rated breaking strength in excess of 1800 pounds, with a net tether diameter of approximately 3mm [4]. A plastic fiber optic core was chosen for its relatively low sensitivity to bend radius.

A commutator plate and brushes within the retractor allow an infrared transmitter mounted within the rotating reel to transmit commands from stationary circuitry. The transmitter is an Industrial Fiber Optics, Inc. IR LED model IF-E96. To limit sensitivity to noise, allow multiple command transmission, and prevent false command transmission, a signal encoder/decoder pair is used. The encoder interfaces directly with tactile switches at the retractor and encodes signals on a 38kHz carrier wave. Commands are transmitted by the IR emitter through the fiber optic cable to the IR receiver at the gripper, where they are decoded and executed. The receiver is an Industrial Fiber Optics, Inc. IF-D96 photologic detector.

## 4 Future Work

The purpose of this research was exploration of the concept of smart tools as a resource for EVA operations. As such, several improvements are anticipated for system functionality as well as potential broader application of this system. These are as follows:

1. A method of reducing moments produced at the anchor by the rigid gripper handle when tangential loading exists. A pivoting handle or other solution that accommodates non-axial loading is highly recommended.
2. A redundant gripper safety lock. Although the lead screw is self-locking, accidental motor activation would open the jaws and must be prevented.
3. Manual gripper operation.
4. Jaw coating to increase friction between the gripper and anchor, protect anchors from marring, and conform to gripped anchors and increase contact area.
5. Easy battery access. For the sake of simplicity of the initial prototype, both the retractor and gripper of the initial prototype require disassembly to replace batteries.
6. Bi-directional communication between the retractor and gripper with user interfaces at both units to improve functionality. This would allow more diverse applications, such as an equipment tether or winch device. Remote control of the retractor friction brake would also be needed for these functions.

Final manufacturing, testing, and evaluation of the prototype system are currently in progress. The resulting data will help determine the suitability of the proposed system as well as reveal unexpected problems that need to be resolved in future design revisions.

## 5 Conclusions

An automated tether system for use in micro-gravity has been researched, designed, and prototyped. The system features a remotely controlled gripper capable of grasping a variety of anchors, a retractor capable of active or passive behavior, and a fiber optic communications channel integral to the tether that transmits commands to the gripper. A prototype of the system is being constructed and testing and evaluation of the system are ongoing.

## Acknowledgements

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## References

[1] Mission Operations Directorate, EVA Robotics and Crew Systems Operations Office, “Online EVA Tool Catalog,” www4.jsc.nasa.gov/org/df42/ evatoolcatalog/index.htm, Prepared by R.C. Trevino and R.K. Fullerton, 1997.

[2] Discussions with John Cobb, President of Electro-Optical Products, Cortland Cable Company, Inc, P.O.Box 330, Cortland, New York, (607) 753-8276. June-July 2001.

[3] EVA And Crew Equipment Projects Office, “Extravehicular Activity (EVA) Hardware Generic Design Requirements Document,” NASA Doc. No. JSC-26626A, prepared by D. S. Adlis, May 15, 1995.

[4] Mission Operations Directorate, Training Division, “EVA Tool Catalog”, NASA Doc. No. JSC-20466, Prepared by R.C. Trevino and R.K. Fullerton, Nov 1985.

[5] Mahalingam, S., Sharifi, M., Dwivedi, S. N., and Vranish J. M., “Special Challenges of Robotic Gripping in Space,” Proc. of the 20th Southeastern Symp. on System Theory, 1988, 581 –586, 1988.

[6] Biagiotti, L., Melchiorri, C., and Vassura, G., “Position/Force Control of an Arm/Gripper for Space Manipulation,” 2001 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics Proc., 2:1175-1180, 2001.

[7] Arisumi, H. and Komoriya K., “Catching Motion of Casting Manipulation,” Proc. of the Int. Conf. on Intelligent Robots and Systems, 2000 (IROS 2000), 3:2351-2357, 2000.

[8] Arora, Jasbir S., “Introduction to optimum design.” New York: McGraw-Hill, 1989.