Conceptual Design of an Extendable Rope-Inspired Module Space Orbit Arm for Maneuvering: ERM-SOA

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Abstract

The space orbit arm comprises rigid links with long length and a fixed working volume that limits its maximum reachable distance. Due to a rigid and long arm structure, the transfer of the contact impact momentum to a floating Space Orbit Arm (SOA) system causes the collision between the arm end-effector and the target object. To mitigate the limitation of the space orbit manipulator, we proposed the conceptual design of a deployable and extendable rope-inspired modular space orbit arm (ERM-SOA). The arm has a radius and the humerus link with 7 DOF like a human arm. The arm links are designed as a rope-inspired structure incorporated with a multi-strand parallel twisted-scissor mechanism to make it extendable. The twisted structure enhances its strength with flexibility. The arm is designed modular by introducing several metamorphic modules for easy scalability without affecting conventional scissor fundamentals. The arm is designed and tested for its functionality in 3D modeling software. The proposed design and fundamental simulation results have shown that the arm can change its working volume according to the applications. The proposed arm may minimize the transfer of contact impact momentum caused by the contact between the end-effector and the target object due to the structure variable stiffness. The ERM-SOA acts like a soft arm due to its variable stiffness. Furthermore, the ERM-SOA also has a protective soft hose cover like human skin to protect the arm itself from debris collision, high temperature, and radiation. We developed a prototype to check its feasibility and it shows extendability without mechanical singularity. Overall, the proposed design concept of ERM-SOA may help to develop an extendable soft space orbit arm for present and future NASA missions and applications.

Introduction

Space manipulator robotics has played a significant role on the International Space Station (ISS) used for many operations, including berthing spacecraft, space station assembly, astronaut positioning, payload transfer, satellite deployment, and spacecraft inspection before reentry. In addition, new missions and applications are being considered, such as asteroid retrieval and redirection, asteroid mining, satellite servicing, and small payload delivery to space stations that can benefit from long-reach manipulators. Three manipulator systems have been deployed in space: the Canadian Mobile Servicing System (MSS), the Japanese Experiment Module Remote Manipulator System (JEMRMS), and the European Robotic Arm (ERA) [1-3]. The MSS includes the 17-m long with 7 degrees-of-freedom Space Station Remote Manipulator System, JEMRMS 10-m long with 6 degrees-of-freedom and ERA is 11-m long with 7 degrees-of-freedom.

The state-of-the-art in long-reach space traditional manipulators incorporates rigid links connected by rotary joints that include motors, gearboxes, and brakes. The rotary joints account for 85 to 90 percent of the manipulator mass and compliance in response to an applied load [4]. The long booms result in restrictive packaging options and adding joints to improve packaging would incur an extremely high mass penalty. The high mass associated with the joints also results in practical limits to reaching, packaging, stiffness and tip force that can be achieved with the conventional architecture.

Recently, an invention of a novel modular space robotic manipulator, Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) has been developed [5-9]. TALISMAN has a combination of lightweight

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truss links, a novel hinge joint, tendon-articulation and passive tension stiffening that the new robotic manipulator architecture achieves compact packaging, high strength, stiffness and dexterity while being very lightweight compared to conventional manipulators. It is easy to scale for different reach, load and stiffness requirements, enabling customization for a diverse set of applications. TALISMAN uses several actuators for tendon actuation that are installed in a semi or fully antagonistic fashion. These actuated cables provide a variable stiffness structure to minimize the arm's collision impact with a floating spacecraft. However, many actuators lead to complex design, bulky structure, control issues, high cost, and working volume fixed once deployed in space, limiting its workspace. Compared to other space manipulators, such as the Shuttle Remote Manipulator System and the Space Station Remote Manipulator System, a TALISMAN with equivalent stiffness in the plane of the cables provides an order of magnitude reduction in mass and nearly an order-of-magnitude reduction in a packaging volume. However, it has variable stiffness only in one plane due to the several cables. So, it can not resist the transfer of contact momentum to the floating space station in the 3-dimensional space. The SOA requires variable stiffness in all planes also. Therefore, these SOA design problems need to be solved for present and future NASA missions and applications.

In order to enable a long-reach SOA to minimize the impact of the contact forces on the arm and floating spacecraft, it is desirable to improve the SOA by significantly increasing the manipulator’s reach, packaging efficiency, and stiffness while reducing manipulator mass and complexity.

In this paper, an extendable rope-inspired module space orbit arm (ERM- SOA) is proposed as a new space manipulator architecture with a twisted scissor mechanism inspired by a rope structure. The arm has seven DOF like a human arm (shoulder-3DOF, Elbow-1DOF, and wrist-3DOF) to perform manipulation. The arm links (Radius and Humerus) are made of the twisted scissor mechanism called metamorphic module and connected several metamorphic segments in series. These metamorphic module structures are twisted like a rope for introducing structure strength with foldbility. The metamorphic segment structure achieves longer moment arms by changing the link lengths of Radius and Humerus. The arm can change its expansion and contraction length due to the twisted scissor structure. As a result, the arm can increase and decrease its maximum reach with variable compliance.

Conceptual Design of an Extendable Rope-Inspired Module Space Orbit Arm (ERM-SOA)

In this section, we describe a proposed rope-inspired parallel twisted-scissor mechanism (PTSM) and its fundamental components. This design is based on the linkage design approach.

In this section, a parallel twisting of scissor strands in scissor mechanism like ropes, as shown in Fig. 1 is proposed. The separate thin strands are weak, and it can be bent easily. If strands twisted over each other, then a rope may be vital. Suppose the twisting of scissor strands is possible using a single actuator with small bending deformation. In that case, this mechanism may have space applications, such as extendable space arm, debries collecting space robot, etc. It may reduce robot weight and cost as well. Borrowing this concept to the conventional scissor mechanisms leads to redesigning the scissor mechanism without affecting the scissor's fundamental.

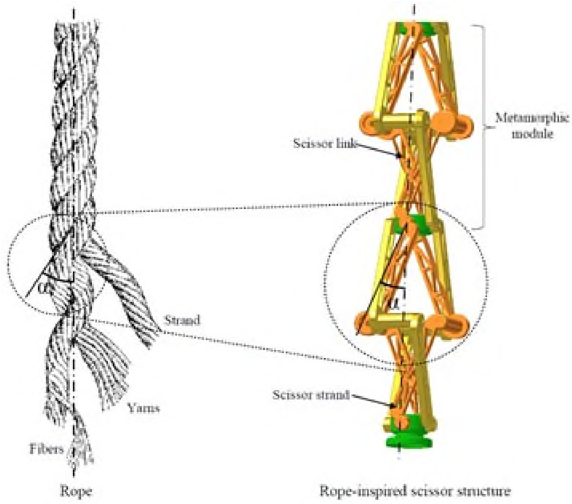


Figure 1. Rope-inspired scissor structure

S-shape linkage design approach

A core aspect of the PTSM design philosophy is the use of two scissor structures in such a way to twist on each other by redesigning links and revolute joints. An S-shaped linkage and a circular connecting node having multiple revolute joints were designed. The S-shape link has a connecting pin with a V-notch passive self-locking feature, as shown in Fig. 2. One side of the link has a revolute joint with a ball bearing, and another end has an extruded revolute joint for connecting S-shape links in series.

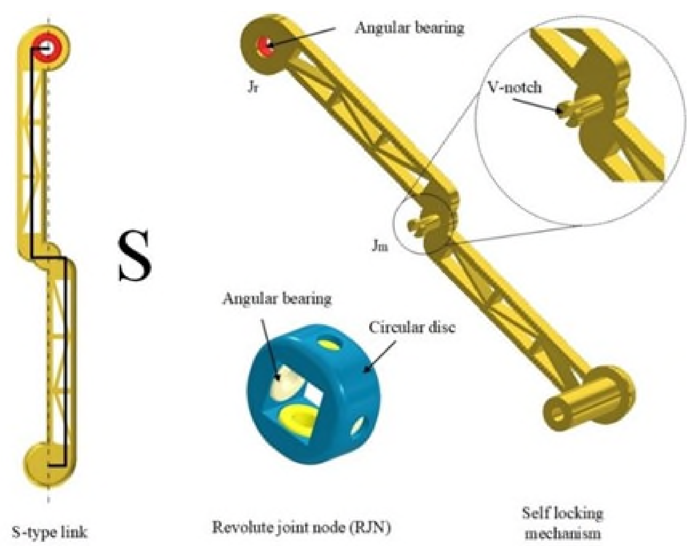


Figure 2. S-shape linkage design approach

Construction of a metamorphic segment

The metamorphic segment consists of multiple S-shape links, connected through revolute joints on the circular node by pressing the link. Metamorphic segments are shown in Fig. 3 for two and four S-shape links. Every segment has multiple S-shape links (see Fig 3(a), prismatic view) in a cross fashion (see Fig 3(b), top view) and is placed orthogonally in X-Y and Y-Z planes. The numbers 1, 2, 3, and 4 in the circle stand for the number of S-shape scissor links. This segment is symmetrical about the center of an axis passing through the circular node, and each link has a variable angle of α, called a scissor angle (see Fig 3(c), side view). The scissor angle decreases as the structure unfolding increases. The S-shape link and circular node are easily connected in series.

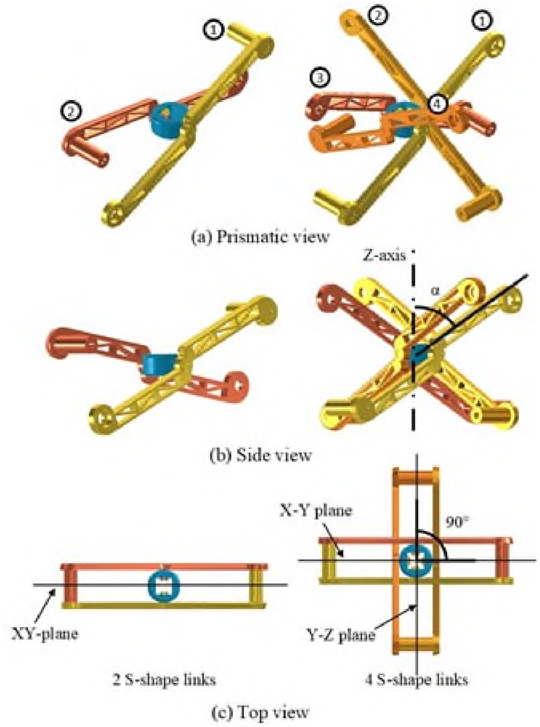


Figure 3. Single metamorphic segment of multiple strands rope-inspired twisted-scissor mechanism

<u>Construction of multi-strands metamorphic link of the space arm</u>

We designed a metamorphic link in such a way that allows multiple scissor links to twist on each other like a rope. The proposed design has a strand-like rope. The multi-strands extendable link has a train of metamorphic segments. The segment has S-shape links connected to the revolute joint node. These are connected through revolute joints, as shown in Fig. 4. In the figure, a 4-strand parallel twisted-scissor mechanism is presented. Every scissor strand has a chain of S-shape links, so we called it a scissor strand.

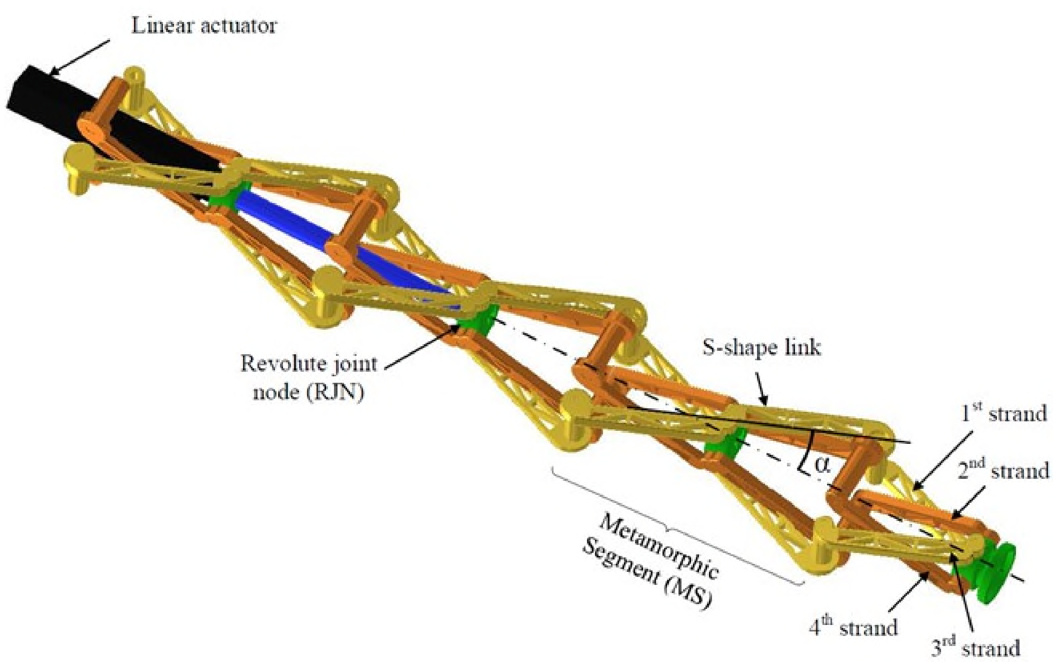


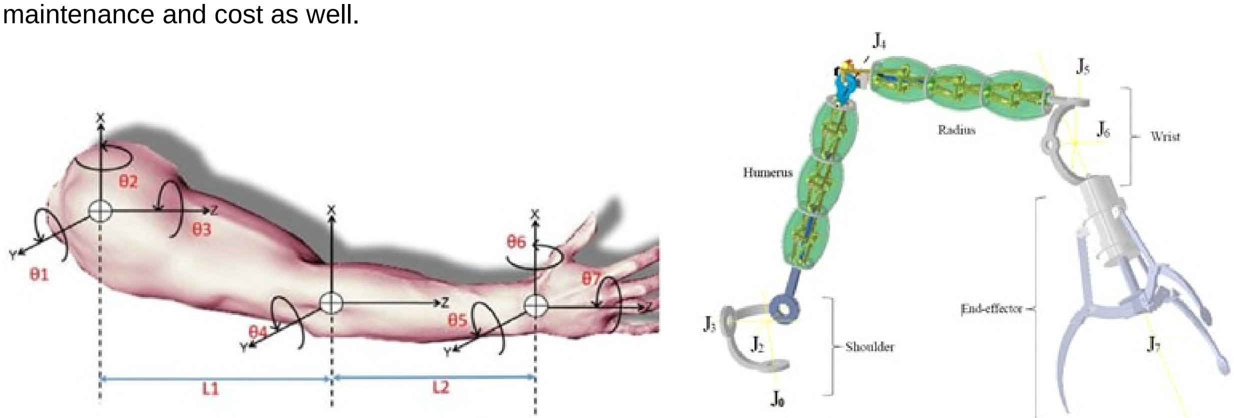
Figure 4. Rope-inspired extendable robot link with scissor angle (α)

This scissor strand is twisted along the axis' center. The proposed design has four scissor strands placed in parallel and twists like a helix. This mechanism is symmetrical about the center of an axis passing through the circular node, and each link has a variable angle of α called a twist angle. The twist angle increases as the structure unfolds and decreases as folding by a linear actuator. A foldable arm's design with longer reachability based on metamorphic link can easily be achieved by adding the metamorphic segments in series also.

<u>Construction of 7 DOF ERM-SOA</u>

- <u>Conceptual design</u>

An entire ERM-SOA motivation is shown in Fig. 5(a) that is inspired by a human arm. The whole structure is like a rope-inspired scissor structure. A long twisted scissor structure is possible to actuate using a single actuator. We propose a 7-DOF foldable rope-inspired space robot arm (shoulder 3 DOF, elbow 1 DOF and wrist 3 DOF) like a human arm for maneuvering, as shown in Fig. 5(b). The proposed foldable arm may improve the end-effector reachability by changing the twisted scissor angle (alpha). The radius and humerus structure has a resistive property against contact momentum transfer. The modular design allows extending the arm's working volume and can be used for multiple applications. It may reduce arm weight, maintenance and cost as well.

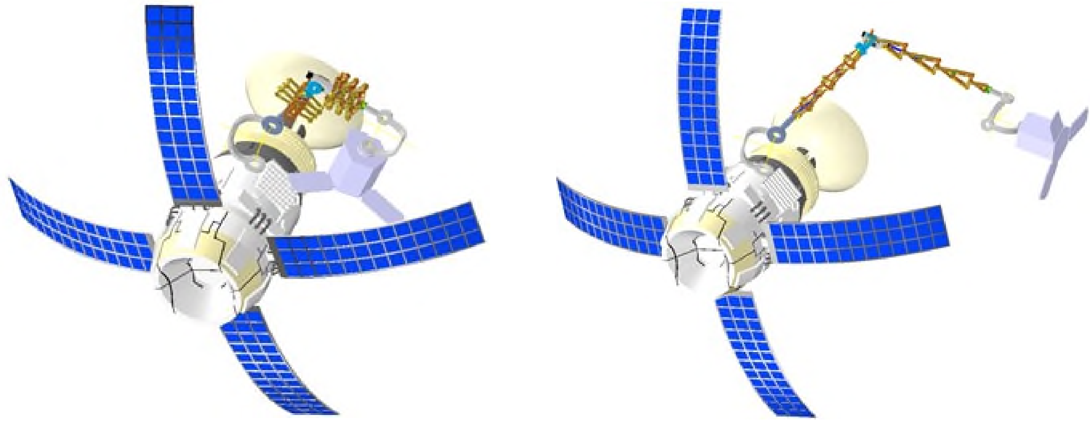


(a) Anatomy of a human arm *(b) Concept of an extendable arm*

Figure 5. Conceptual design of an extendable rope-inspired Module Space Orbit Arm for maneuvering

- <u>Functionality</u>

The basic functionality of the extendable rope-inspired space orbit arm (ERM-SOA) is shown in Fig. 6. The arm has the unique functionality of an adjustable working volume. The arm can be used for small-reach and long-reach maneuvering according to the application. When the radius and the humerus length are fully folded, the arm has a small working volume and small reach (see Fig. 6 (a)). It can be used for close maneuvering to the space station, for example, astronaut positioning on the International Space Station (ISS) for maintenance. If the arm is fully unfolded, it has a large working volume and long reach (see Fig. 6 (b)). It can be used to maneuver far from the space station to avoid collision. For example, to capture a dead satellite or asteroid far away from the International Space Station due to collision avoidance can be done. When the arm is entirely extended, it behaves like a cantilever. The arm has a variable stiffness, and it behaves like a rigid body when it is entirely folded and acts as a soft body when it is entirely unfolded. Due to the variable stiffness, the contact momentum transfer caused by the collision between the arm end-effector and the target object can be minimized. The arm can extend its long reach and capture the moving satellite to avoid the contact momentum transfer to the space station and reduce its reach for precise maneuvering.



(a) Fully folded ERM- SOA (small-raech) *(b) Fully unfolded ERM-SOA (long-reach)*

Figure 6. Functionality of the extendable rope-inspired modue space orbit arm: ERM-SOA (adjustable space arm working volume)

- <u>Protective cover</u>

The proposed arm is covered by a soft hose which is resistive to provide the ability to protect the arm from being damaged due to debris collision, high temperature, radiation, etc. A soft and resistive hose covers each segment module of the arm (see Fig. 7) and the cover is connected to the sequential module by connecting rings that allow us to add or remove the module according to the application. The cover is soft enough to allow the arm's basic functionality, resistive enough to provide the protection against outer debris, and strong enough to increase rigidity in an extended direction. The connection ring with soft cover may increase the strength of the arm.

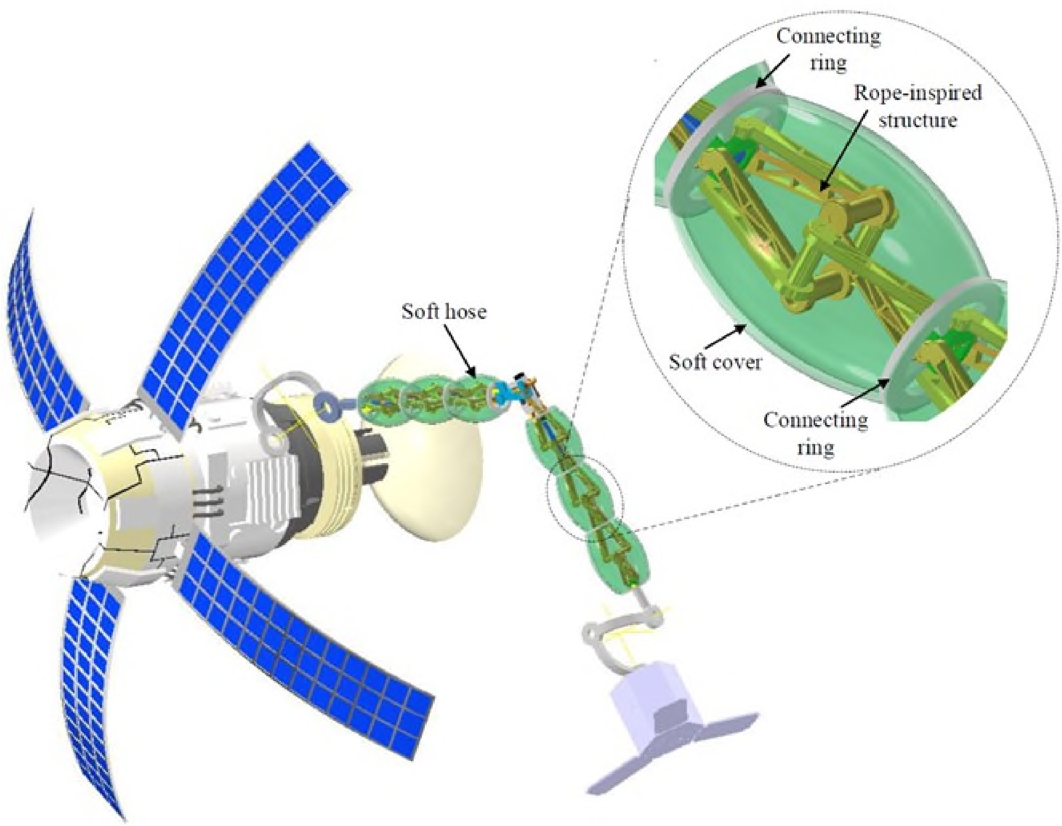
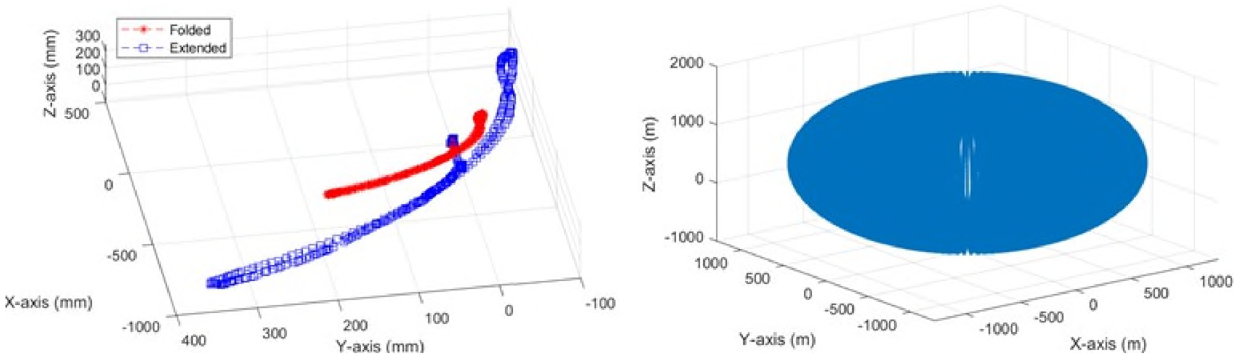


Figure 7. ERM-SOA with a soft protective cover (soft hose cover)

Preliminary Results and Analysis

<u>Extendable maximum reach and working volume</u>

Figure 8 (a) shows the working volume of the ERM-SOA. This is the typical workspace of a robot arm with seven degrees of freedom like a human arm. Three revolute joints intersect at the same point and make a spherical joint like a shoulder joint in a human arm. The arm has two spherical joints one at the shoulder and another at the wrist. The arm has a Humerus and Radius like a human arm with extending capability and extends its working volume as shown in Fig. 8 (b). Therefore, the arm can change its length according to the maximum reach. The arm has the capability to make multiple maximum reach lengths in the space.



(a) variable maximum reach of end-effector (b) Working volume of arm when it was fully extended

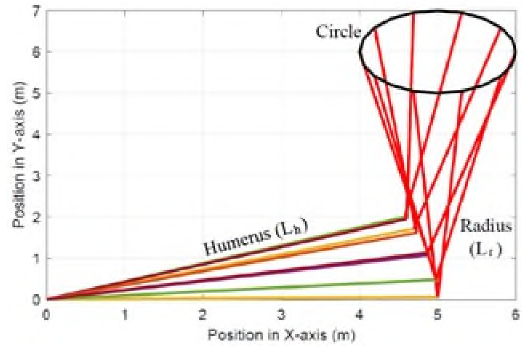
Figure 8. Extended working volume and maximum reach of a ERM-SOA in the space

<u>Variable elbow pose during tracking</u>

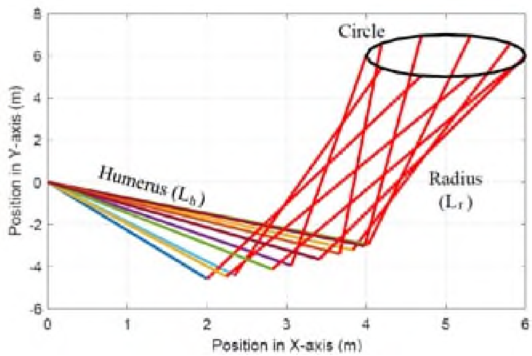
This simulation is performed to check the feasibility of various elbow pose to reach a particular point in the space. Sometimes traditional robots can not reach the target point due to fixed link length. However, the extendable length of humerus and radius length may help to achieve this target. In this subsection, we aim to achieve compliance of a robot manipulator along a predefined path, giving the robot the ability to change its elbow pose while tracking a circular path. Figure 10 illustrates this objective, where the desired path is a fixed circle, the links humerus and radius change their length to keep tracking circular path. In the simulation we change the simulated three cases: first for the same Humerus and Radius length (see Fig. 9 (a)); second is when the Radius length is greater than Humerus length (see Fig. 9 (b)) and third is when the Humerus length is higher than radius length (see Fig. 9 (c)). However, in all three cases, the circle path position is fixed (5, 6). The results show that the arm can reach the target point by changing its elbow pose. this capability may use for developing a next-generation space arms with enhanced reaching capability.

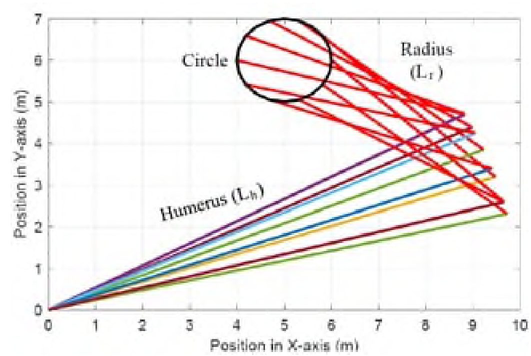
<u>Impact analysis</u>

The impact force propagation in the structure is a significant problem in developing long space arms. The impact force may destroy the long space structure and floating station. In order to see the impact effect on the proposed space arm, We created a simulation environment in Autodesk Inventor design software, as shown in Fig. 10. The impact force of 10 N was applied to the structure and observed the deformation. The deformation is small (in X-axis 6.91 mm, Y-axis 3.78 mm and Z-axis 7.75 mm) for long extension (700 mm). The proposed twisted scissor structure behaves like a foldable cantilever so that deformation behavior makes the structure compliant and soft in nature. The simulation results show it has the capability to withstand the impact force and compensate the impact force. The overall simulation results suggest that rope-inspired scissor links may help for making large space structures in the future.



(a) Circle tracking with same length of Humrus and radius length of the ERM- SOA





(b) when Radius length is greater then Humrus (c) when Radius length is greater then Humrus

Figure 9. Simulation of a variable pose of ERM-SOA while tracking fixed circle

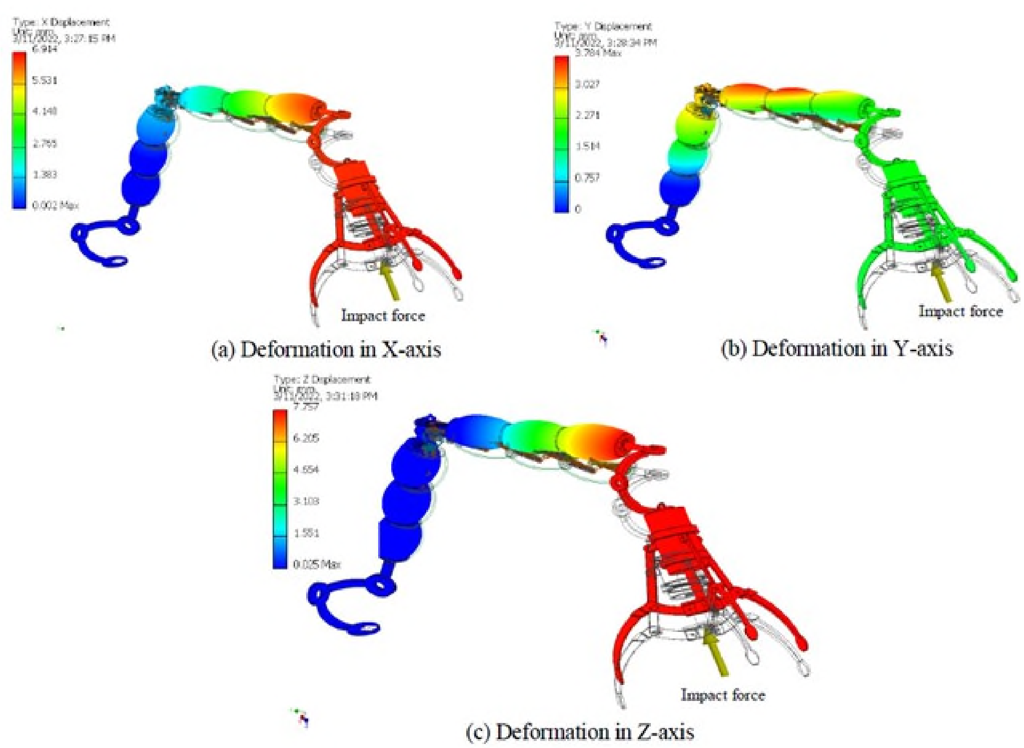


Figure 10. Deformation of a ERM-SOA due to impact force of 10 N at the end effector

Prototype development

We developed a prototype of a rope-inspired extendable link to check its feasibility and functionality as shown in Fig. 11. The scissor strands are twisted on each other and align with the central axis. The black strand is printed in black to observe its basic feasibility. We observed that the extendable rope-inspired structure was able to extend and contract using a single actuator. When it extended, it shows bending under gravity. However, the bending is pretty low as compare with the traditional extandable scissor structure (see Fig. 11). In case of a space application, due to the absence of gravity this structure may be useful. Therefore, the preliminary results shows the capability to use it as a foldable link in space robot arm. We also tested introducing multiple metamorphic segments to make it more longer. The most exciting finding was that our proposed design has a unique feature of several self-locking feature to avoid singularity without using additional sensors or mechanism or control. All links automatically locked themselves to each other and the structure cannot extend further (see the prismatic and front view in Fig.12). Each link's end is connected uniformly in a square shape, which is a hollow square beam. The PTSM allows smooth full extension and full contraction. The good news is that PTSM never gets a bending singularity due to the symmetrical structure along the central axis. In our experiment, we observed that it does not depend on the metamorphic segment. We used four metamorphic segments and fully extended. If we increase the number of metamorphic scissor segments, it bends more but never gets the bending singularity.

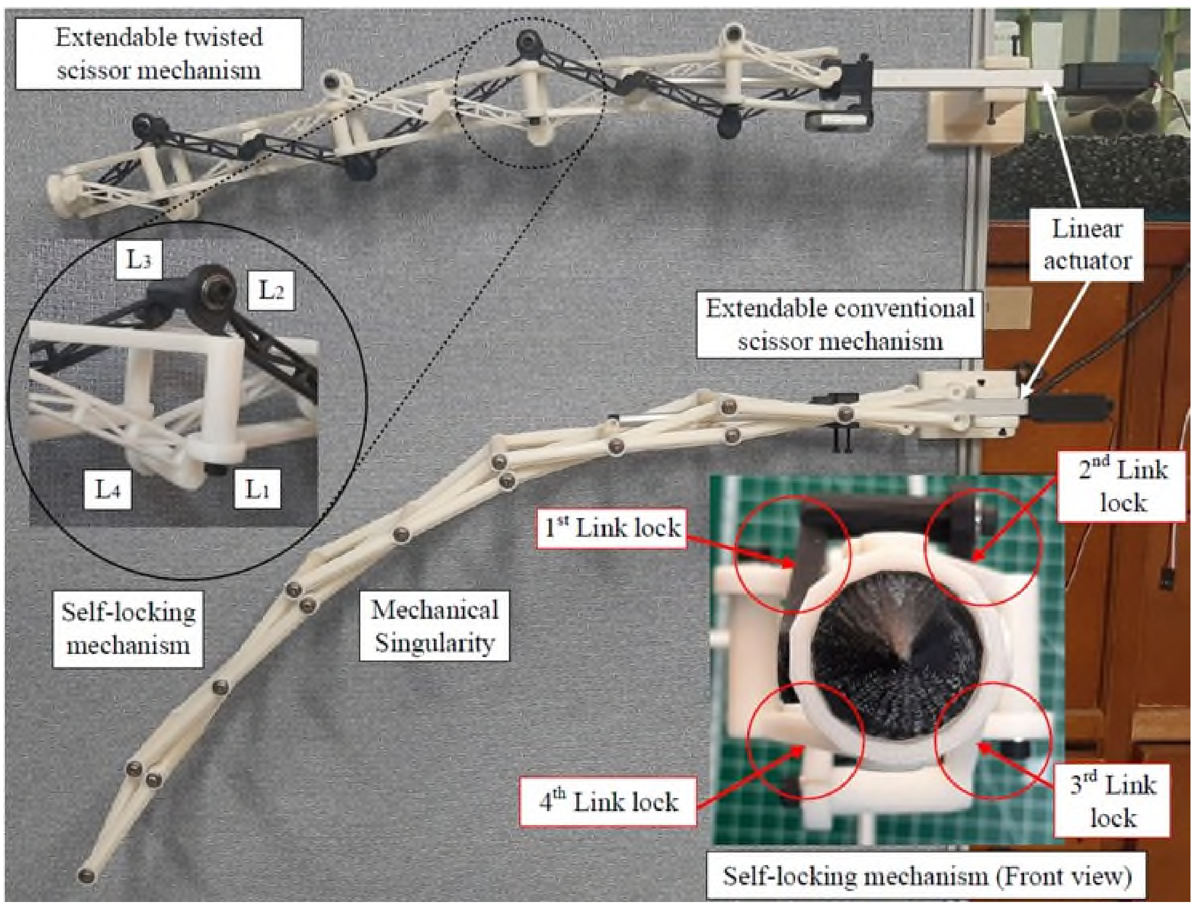


Figure 11. Propotype development and feasibility test of rope-inspired structure

Advantages of the ERM-SOA and Applications

Advantages

The key features of the new ERM-SOA are:

- Extendable links (radius and humerus) due to twisted-scissor structure with major components being the lightweight link, truss and connectors,
- A single actuation actuates the deformable structure (radius or humerus),
- Extendable working volume; arm has a variable working volume due to foldable links,
- Modularity; arm length and working volume are easy to scale due to metamorphic modules without adding any additional actuators,
- Self-locking structure without a mechanical singularity,
- Protective soft hose protects the arm from the external environment and increases manipulator's stiffness,
- Lightweight and hollow structure allows optimized packaging efficiency, range-of-motion, dexterity, etc.,
- Structure has a variable stiffness that decreases as structure grows and act as a soft link,
- Structure may reduce impact momentum transfer from end-effector to floating station due to decrease in the stiffness,
- Arm requires small space in the launching rocket due to folding capability.

Applications

- Present applications

The proposed extendable space arm has enormous potential for present and future space applications due to adjustable long-reach maneuvering such as astronaut positioning, payload transfer, berthing spacecraft, space station assembly, satellite deployment, and spacecraft inspection before reentry. The space manipulator reach can be adjustable according to the application requirement. For example, the proposed arm can grab a payload and drop it into spacecraft.

- Future applications

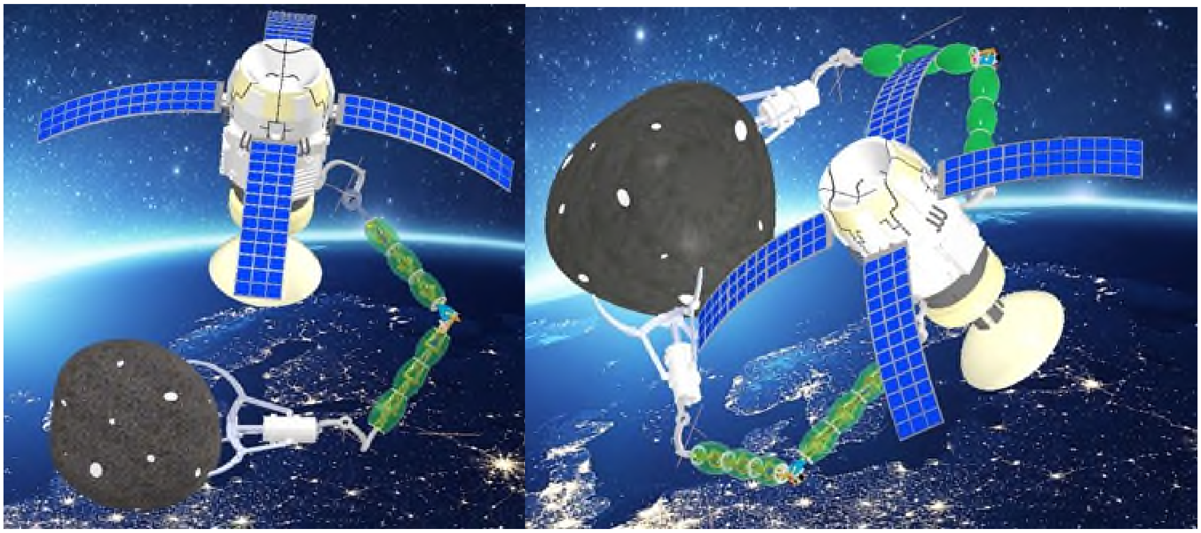
Future NASA missions and applications are being considered, such as an asteroid collision avoiding system, asteroid retrieval, redirection, asteroid mining, dead and active debris capturing that can benefit from long-reach manipulators with its momentum transfer resistive property.

- Asteroid collision avoiding system

A new application of space manipulators has emerged in the future mission as an asteroid collision avoiding, retrieval, and redirection system for International Space Station. This structure may helpful for developing extendable single and multiple space arms, as shown in Fig. 12. The long-reach based on the proposed concept may deploy on the ISS for large asteroid capturing and diverting it before the collision occurs with the ISS or any space station.

- Space debris collection at ISS

Currently, active debris removal has become a more urgent application, so the proposed extendable arm may be helpful to track, capture and collect debris. The major problem of capturing active debris is the momentum transfer to the floating capturing system due to collision between arm end-effector and target debris, which may cause losing tracking path itself. Due to the variable arm stiffness, the proposed space arm may minimize the momentum transfer to the floating capturing system.



(a) Single space arm for capturing dead debris (b) Multiple space arms for capturing dead debris
Figure 12. ERM-SOA-based debris collection space robot system

- o Dead debris capturing

The earth is surrounded by a lot of debris, and it is a crucial issue of capturing and dumping them. The proposed extendable space arm can capture debris before reaching enough close to the floating satellite due to its unique feature of extendability. In addition, the proposed arm is module-based, so the maximum reach can be increased simply by adding more modules in the space arm. Therefore, the floating capturing satellite may be safe and out of risk of debris collision, as shown in Fig. 13.

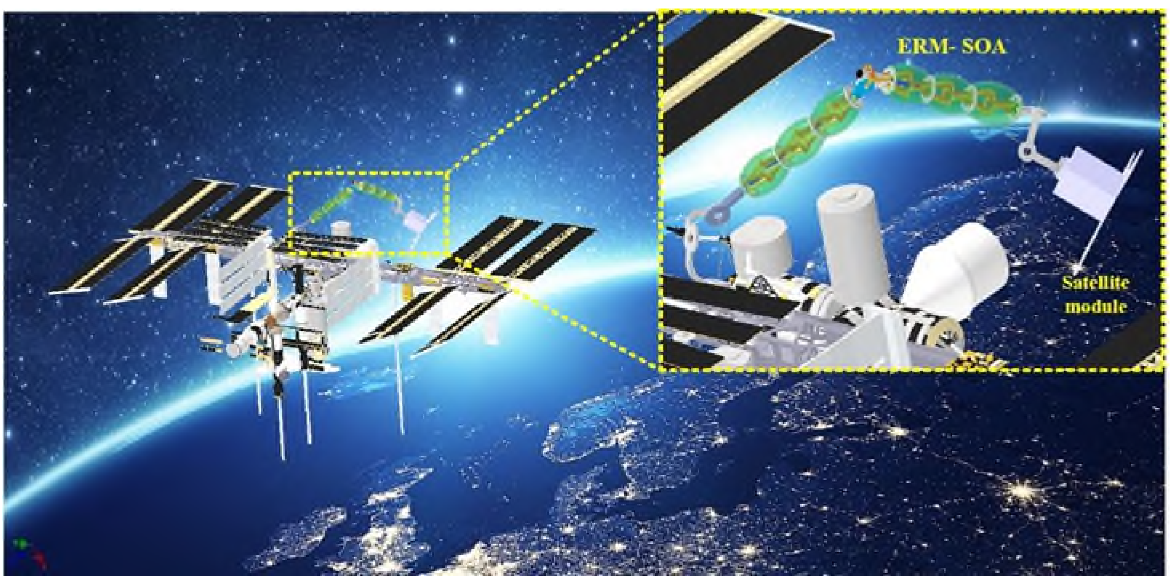


Figure 13. Space debries capturing and diverting from ISS using an ERM-SOA

o Manipulation in space for maintenance and assembling operation

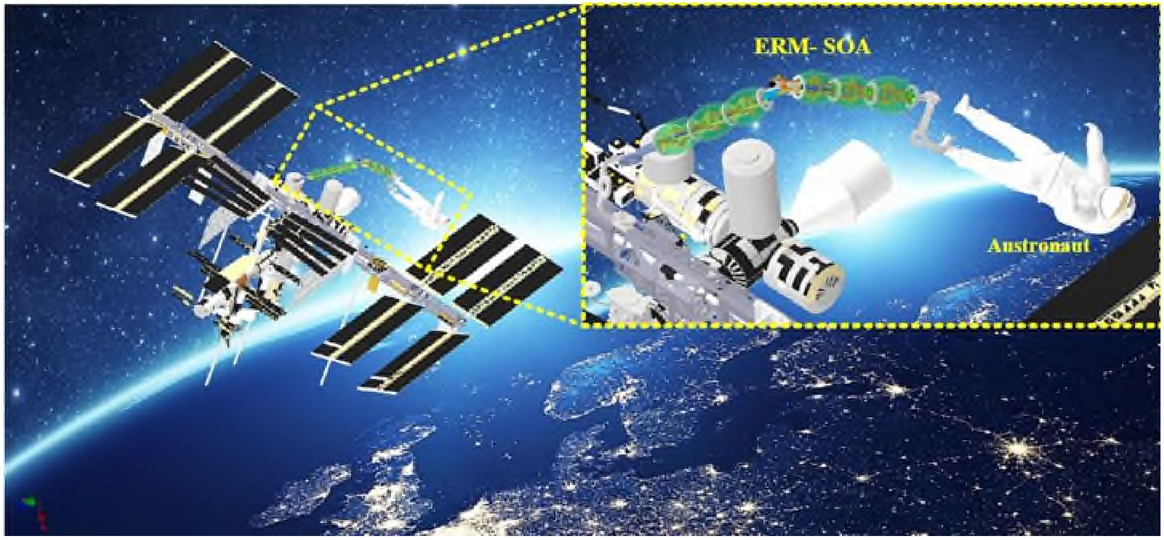


Figure 14. Astronauts with ERM-SOA for inspection and maintenance of solar panels.

At the International Space Station, the space robot arm performs several operations such as inspection, observation, maintenance, assembling, etc. In these operations, the working volume is the key requirement to perform these operations in the space. The traditional space robot arm has limited working volume and it can not enhance it after installation. Therefore, traditional space arms can perform space operations in a limited working volume. For reaching every point of ISS, one needs to install multiple space robot arms, which make the system more complex, require large maintenance, and increases mission cost.

To solve these challenges, we propose an extendable space arm and install it on the ISS at the optimal location from which the space arm is able to cover maximum ISS outer space for performing space operations (see in Fig. 14). During the space operation contact between two bodies, that contact geometry is characterized as three cascade peg-in-hole pairs (one rectangular peg/hole and two cylindrical pegs/holes). This is just one of many batteries of different sizes and designs on ISS, which have been maintained by either EVAs or the dual arm ISS robot Special Purpose Dexterous Manipulator.

Generally, space operations like maintenance and assembling create contact impact between the robot boom and ISS surface. The insertion or removal of such a battery into or from its housing worksite was one of the most difficult operations of the ISS robot. All capture and some manipulation operations involve physical contact between the robot arm and an external object or the environment. Contact operations are among the most difficult operations for a space arm, whose contact behavior is governed by contact dynamics. The proposed arm has the capability to change its stiffness with the extension of the arm. It behaves like a cantilever when it is fully extended which absorbs the vibration due to contact between two bodies. This may help to allow performing operations more accurately. It may enhance the maintenance cycle of the robot itself.

Conclusion and Future Work

This work presented a novel mechanism design approach for the preliminary design of an extendable rope-inspired module space orbit arm for maneuvering in space. The arm has 7 degrees of freedom like a human arm. The metamorphic segments were designed using the S-shape linkage design approach to develop a module-based arm using multiple twisted parallel scissor strands like a rope. This metamorphic parallel twisting mechanism has been introduced in the scissor mechanisms, called rope-inspired scissor mechanism. The arm can contract and extend its maximum reach of the end-effector. This linkage design approach does not affect conventional scissor fundamentals. However, it enhances the strength and modularity of the structure. It has shown better performance than a conventional scissor. It does not get a bending singularity in the fully unfolded configuration and is independent from the number of metamorphic segments. Considering all of this evidence, it seems that a rope-inspired scissor mechanism is a suitable candidate for deployable and reconfigurable mechanism. Another significant result is that it requires only a single actuator for multiple strands, making the rope-inspired scissor mechanism lightweight and cheap. The arm behaves like a cantilever while fully extended. The extendable compliant structure may absorb and compensate the impact forces during contact between end-effector and object. The approach was applied to the design of an extendable space robot for maintenance, inspection, and assembly on the ISS.

In future work, we will develop the hardware of 7 DOF rope-inspired arm and perform manipulation operation in zero gravity environment. Future work also includes experimental evaluation of the impact forces on the proposed space arm.

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