Scaling Climbing Collaborative Mobile Manipulators for Outfitting a Tall Lunar Tower and Truss Structures

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In-space and planetary truss structures like the Tall Lunar Tower (TLT) can greatly benefit from truss climbing collaborative mobile manipulators (C2M2) for outfitting and other servicing tasks. Mobile robotic systems traversing truss structures will allow for improved access to the structure for placing equipment and routing cables after the structure has been assembled. The C2M2 is designed to provide access to the structure through collaborative mobile robotics. A series of gaits are developed allowing the robot to reach any point on the structure and validate the capabilities of the joint configuration. Scaling the system during the design phase is a necessary process, given the wide range of trusses in development and payloads which are required for outfitting. The variable features of the system are the actuators and the length of the links connecting the two degrees of freedom (DOF) modules. A scaling method was developed for determining the range of usable link lengths for a selected actuator in a design environment. The focus of the design is on a six-DOF robot arranged with two DOF at each end and at the center. Two grippers are mounted at each end for grappling on the truss and holding cargo.

I. Nomenclature

L = Link length
r_g = gripper radius
r_n = node of truss radius

II. Introduction

As larger structures are assembled in space, trusses are an attractive building framework for their structural efficiency. Construction and outfitting of these in-space assembled truss structures will benefit from robotic agents where astronauts are unavailable [1]. Most existing in-space assembled truss architectures are focused on the construction of the truss structure [2-5] but once constructed there is a need to outfit the structure to be fully operational. During concept development for Space Station Freedom (SSF) which preceded construction of the International Space Station (ISS), outfitting of a truss structure with cabling and payload modules were identified as needed capabilities [6]. The complexity of completing outfitting operations with the technology available in the late 1980s and early 1990s contributed to the selection of pre-integrated truss segments for the ISS. A seven degree-of-freedom (DOF) robotic arm called the space station robotic manipulator system (SSRMS) was adapted from the shuttle robotic manipulator system (SRMS) to support the construction of the station. The SSRMS was designed to allow for

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traversal of the station between nodes on the structure which provide power and data connections to the arm via identical end effectors on either end of the robot [7].

Generalized truss climbing robots have been developed for both surface and orbital applications. Example truss climbing robots include Shady3D[φ] [8], Bill-E [9], and the Self-Mobile Space Manipulator (SM2) [10]. Shady3D is an underactuated three DOF robot for climbing trusses and demonstrates the capabilities of a small system for traversal of a structure. Shady3D can move independently or interface with a second Shady3D robot to form a six DOF collaborative system. Bill-E uses truss voxels and teams of robots to move the voxels across large structures comprised of those voxels. The Bill-E robot demonstrates the capabilities of collaborative robotic systems moving external to a structure. To traverse SSF, the seven DOF SM2 was developed to demonstrate internal and external locomotion on the structure.

Related terrestrial collaborative and mobile robotic systems have been developed showcasing the versatility of such a system. A one DOF robot module has been demonstrated for assembly of timber structures [11]. A team of robots can move timber sticks into a final configuration as a distributed network or collaboratively team to construct a conventional serial manipulator using the timber as links. A mobile six DOF robotic arm referred to as a Latching Intelligent Modular Mobility System (LIMMS) [12] has been demonstrated collaboratively transporting boxes using wheels at the ends of the robot. This allows for driving to increase efficiency of locomotion. Once a box is delivered the team separates and drives independently.

To fill the niche of providing a robotic system to outfit the inside of truss structures and collaboratively move cargo, a climbing collaborative mobile manipulator (C2M2) is being developed. The C2M2 is a robotic system designed for use on the Tall Lunar Tower (TLT) engineering development unit (EDU) under development at NASA Langley Research Center (LaRC) [3]. C2M2s will complement the TLT design by enabling the placement of additional equipment after construction, and further adaptation to the requirements of a lunar settlement. Other truss geometry and structures developed nearby can be supported by the same robots given a system is scaled properly.

III. Applications of the C2M2

In-situ assembled truss structures will require dedicated robotic systems for construction and outfitting. Assembly of truss structures will require robotic systems for placement and joining of struts. Systems which can traverse a truss structure will allow the system to be upgraded and outfitted with new equipment after construction. Currently, the level to which outfitting is necessary can be varied depending upon the extent to which components are pre-integrated to the system. Once in-situ resource utilization is realized for structural applications, outfitting will be necessary to create a useful structure out of components with no pre-integration. Assembly of truss structures will require robotic systems for placement and joining of struts. Systems which can traverse a truss structure will allow the system to be upgraded and outfitted with new equipment after construction. Currently the level to which outfitting is necessary can be varied depending upon the extent to which components are pre-integrated to the system.

The ISS was assembled in space but required minimal outfitting as most of the systems were installed while on the ground. When building large structures with construction sites located beyond low Earth orbit (LEO), the benefits from outfitting are increased. Although there is significant investment in robotic systems and infrastructure to support the construction of the structure and outfitting, the cost can be depreciated across multiple structures or a large-scale structure if the robotic systems are ubiquitous enough to be used for multiple construction projects. Long term use of the construction infrastructure makes construction of persistent sites using in space assembly methods appealing. The robotic systems used during construction can support the mission of the platform or outpost post-construction. Some structures which are envisioned using robotics for both construction and operation are outlined in [1] including space telescopes, interplanetary vehicles, and orbital docks. On the surface of celestial bodies, a similar concept of operations is outlined in [5]. Several of these applications are shown in Fig. 1 including TLT (Fig. 1a), the in-Space Assembled Telescope (iSAT) being developed by the Precision Assembled Space Structures (PASS) project (Fig. 1b), and Lunar Safe Haven (LSH) (Fig. 1c). The TLT will have a need for servicing robots to increase the capabilities after construction to ensure the TLT can meet the demands of the dynamic lunar settlement. Additionally, after construction in all these applications, C2M2s can be used for inspection and repair of struts and discrete components.

[φ] "Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the analytical tools used. The use of vendor and manufacturer names does not imply an endorsement by the authors nor does it imply that the specified equipment is the best available."

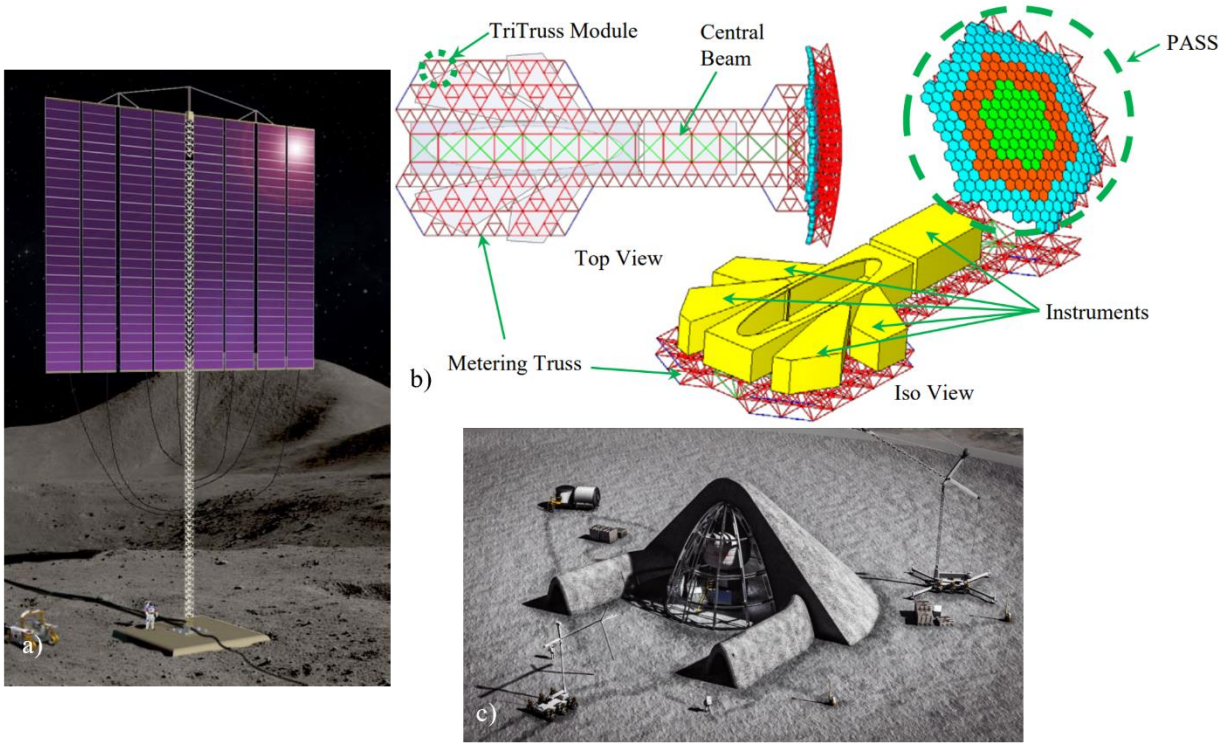


Fig. 1 Example space infrastructure supported by C2M2s, a) TLT [3], b) iSAT supported by a PASS [4], c) LSH [5].

To provide outfitting capabilities to a structure the C2M2 must be able to reach key areas to place utilities and payloads. The geometry of the structure determines the minimum DOF and joint configuration which can reach any location on the structure. There is a wide range of truss geometries in use for space applications ranging from tri-trusses in use on projects such as PASS [4], hexagonal voxels, and cubic trusses with diagonals used in the TLT. A robotic system is presented in this paper focused on supporting the TLT. Given the complexity of navigating the diagonals of the TLT truss a system which can traverse the TLT should be capable of also traversing other structures currently in use with development of additional gaits.

To traverse a structure, the robot will need grippers designed to interface with the struts. Once large-scale infrastructure is established in space, standardized strut dimensions in an application area would allow for more versatility of the systems developed for use with multiple truss structures, similar to the development of cube sat standardization [13]. Standardization would simplify the ability for C2M2-like systems to transfer between structures designed by different groups and constructed at different times without the need for unnecessarily complex adaptable grippers or extra grippers to be supplied.

The utilities supported by C2M2 robots can vary drastically depending upon the structure being supported. The TLT is envisioned to be supported primarily in providing a method to outfit the tower like cell towers on Earth which require frequent upgrading of antennae as wireless communication systems improve and the demand of an area increases. Without the C2M2, either the structure would only be usable with the initial equipment installed or a dedicated robot system would be permanently installed on the structure to provide upgrades. For in-situ resource utilization to be realized robotics are necessary to first construct a structure from the raw components produced and then place components on the structure to make them usable. The C2M2 provides a system which can be adapted to meet the role required by the outpost or construction site.

To support the wide range of outfitting and construction tasks required to build space infrastructure the C2M2 would be benefited by a set of tools similar to those developed for the Lightweight Space Manipulator System (LSMS)[14]. For construction the collaborative capabilities of the C2M2 can be leveraged by replacing one gripping end effector with a tool and grapple point. In this configuration, a one robot can have a bulky tool attached such as a welding or cutting tool and move with a second robot to operate as a biped. Additional tools can be developed to interface with the strut grippers or an additional interface on the robot. For large construction operations, C2M2s are dedicated to

niche applications with pre-integrated tools such as welders or nondestructive testing equipment could improve capabilities.

IV. Overview of Robotic System

The requirements for the C2M2 were developed to best support the TLT and other infrastructure developed around the TLT truss design. Primary goals of the outfitting included capabilities to collaboratively move cargo and traverse the structure independently. Independent operation is not a necessity for collaborative robots however, this allows for more versatility and generalization of the robots. Cargo was generalized as discrete rectangular prisms similar to cube satellites [13] which have become a standardized geometry for small satellite buses. The addition of a gripper which can both interface with trusses as well as efficiently carry cargo and tools is an area of future work. Currently, the design space only requires a gripper which can grasp the strut and specialized interfaces on the cargo modules.

The C2M2 design shown in Fig. 2 was developed to support the TLT truss. A semi-symmetric system was selected with six DOF, from three two-DOF modules, shown in Fig. 2c, one on either end, the wrists, and a central module, the elbow. Connecting each wrist to the elbow is a body link, sized to make the distance between wrist and elbow modules equal on both sides. On the current scale model, the body link is simply a structural member, however, in a full-scale system the link would house the control electronics and batteries for the system. Each end has a gripper actuated by a single micro servo shown in Fig. 2b. The gripper interfaces with square struts and specially configured payload modules. The gripper fingers can be replaced to change the strut size being grappled and the entire gripper can be replaced if a new gripping mechanism is developed.

A robotic demonstrator was designed to provide a testbed for development or gaits, motions the robot makes to move across a truss, and provide a visual of the system. MG90S micro servos were selected as actuators due to having low mass, low cost, and high torque to weight ratio. The MG90S micro servos were used for all six DOF actuators and the two grippers. The grippers were scaled to grip 1 in. square aluminum tubing for testing. A second set was scaled to interact with the 0.83 in. square carbon fiber struts used by TLT. The modularity of the end effector allows for the two gripper sizes to be easily changed for testing in different environments.

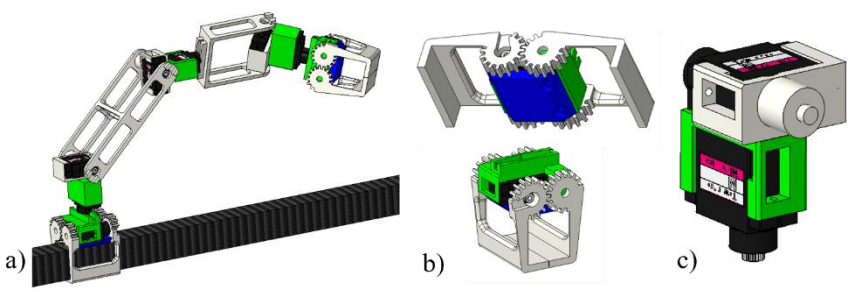


Fig. 2 Climbing Collaborative Mobile Manipulator shown grappled to strut a), gripper module open and closed b), and actuator module c).

The C2M2 developed here is a demonstration of the capabilities of the six DOF configuration. A three DOF wrist used in a seven DOF configuration has the mass of an additional actuator at the end of the arm compared to a two DOF wrist. The two DOF configurations allows for longer body links, or a larger payload capacity. Compared to underactuated systems a six DOF arm allows for more versatility as a conventional mounted robotic manipulator without requiring reconfiguration before use in that role. Despite the aforementioned benefits, two issues are present: asymmetry and reachability limits. The system is not fully symmetric which prevents a simple flip of the actuator order for control when the other end is grappled like used by [10]. Illustrating asymmetry, the robots in Fig. 3 configurations A and B are flipped resulting in the swap of joints 3 and 4. The system also cannot reach all end effector orientations at any end effector position when avoiding obstacles. In free space, the six DOF arm would be able to reach any pose with the end effector at a wide range, but when reaching around struts rotation of the end effector requires motion further up at the elbow increasing interference. Both the symmetry and reachability are solved by a seven DOF configuration with three DOF wrists. For the envisioned TLT application a six DOF system provides ample pose control, mobility on the structure, and increased payload capacity to allow demonstration in terrestrial gravity.

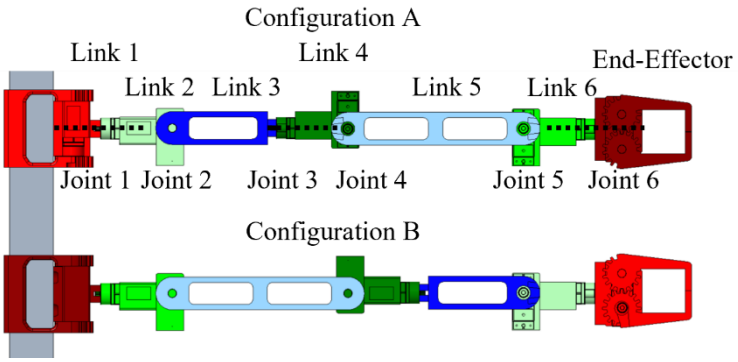


Fig. 3 The two potential joint configurations are show dependent on which gripper is used as the base. Configuration A and B joints 3 and 4 and links 3 and 5 are switched.

V. Gait Development

To move a climbing robot through a structure, a predefined set of motions called a gait, can be defined and repeated when a similar environment is encountered. Here, the gaits are being applied to a truss climbing robot to simplify the development of a method to move across a structure. Traversal of truss structures can be complex when modeling the motion to minimize energy consumption. To simplify the modeling process, a set of gaits are generated, each of which move the robot or pair of robots to a new position on the structure. By combining a set of these gaits or modulating the distance which the gait moves the system, any usable point on the structure is reachable. Final positioning of the payload or gripper can be done assuming the robot as a serial manipulator with the base attached to the truss.

The set of gaits to traverse the TLT truss are shown in Fig. 4 with each motion between numbered bubbles being a different gait or orientation of gravity. These gaits allow for the robot to reach all the struts in the system on any face. For long lines, such as Fig. 4a, 1-2 and 4-5, multiple steps of the gait may be necessary, and the length of the step varied to reach the desired location. For the more complex motions, such as Fig. 4b, 6-7, and Fig. 4c, 11-12, several sub-steps are necessary. The TLT structure with diagonals presents convenient symmetry for the gaits shown in Fig. 4b where all four motions are identical with only the orientation of gravity changing. Motion from one reachable point on the structure to another can be achieved by combining multiples of these motions sequentially.

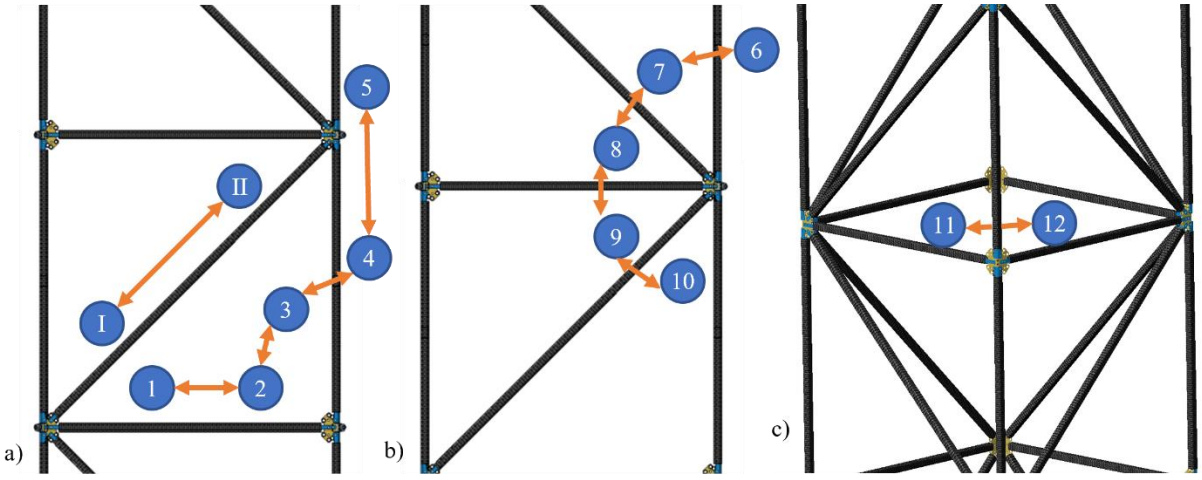


Fig. 4 Motions of robot to fully traverse structure. Standard motion paths are shown in 1-5 and 11-12 in a) and c) Motion around the diagonals is shown in b) with the same steps being taken between 7-6, 7-8, 8-9, 9-10 with only the gravity vector changing direction. In a) I-II uses same handoff procedure as 1-2.

Forward motion of a single robot through the structure as shown in Fig. 4 can be simplified to five motion types. Each of these are shown in Fig. 5. In Fig. 5a, 5c, and 5d the middle of the motion is shown, where the robot starts

sitting on one strut with both grippers on the same side of a strut, then moves the first gripper to a different strut to reach the configuration shown. After grabbing the strut, the second gripper is released and grapples onto the same strut as the first gripper. For motion along or around the same strut, Fig. 5b and 5e show the C2M2 moving forward and to a different side. The motion necessary to move from a diagonal onto a horizontal is shown in Fig. 5a, Fig. 4b 7-8 is shown but can be generalized to all motions in Fig. 4b. Fig. 5b shows a general forward motion, either horizontal or vertical, Fig. 5c shows a horizontal to vertical change, Fig. 4a 2-3, Fig. 5d shows Fig. 4c 11-12, and Fig. 5e shows Fig. 4a 3-4.

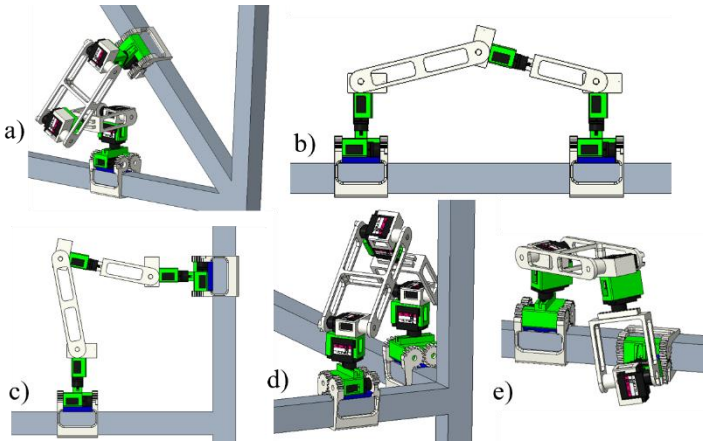


Fig. 5 Middle of motion by solo C2M2 to fully navigate truss.

The main constraining factors for the gaits were produced from the torque limits of the C2M2. The system was designed with a maximum torque condition when a single robot holds the payload out at full extension. If one robot was holding both the payload and second robot, to avoid needing a hand off, complex joint configurations and optimization are required to prevent overloading the actuators. To simplify gait development and increase the robustness, a hand-off is done between the robots with motion only being done by a single robot while the other holds onto the payload as shown in Fig. 6. The controls necessary for the hand-off motion is an area of ongoing development for operation.

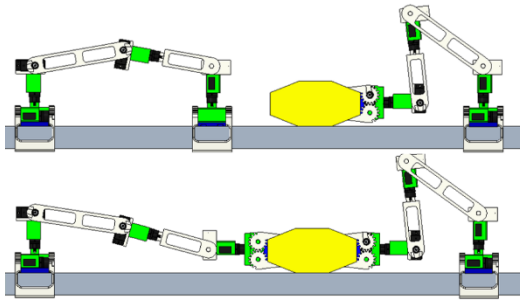


Fig. 6 Demonstration of handoff between left and right robot during a linear motion.

VI. Scaling of Robotic System

The C2M2 configuration presented here can be scaled by varying actuators and link lengths to a wide range of truss structures and payloads. The diverse application window produces a need for methods to constrain the design of the system such that the system can operate on the range of trusses anticipated. Here, analysis is performed on the robot in a static maximum torque condition, where the robot is loaded with the design payload and at maximum extension perpendicular to gravity. As shown in Fig. 7, both joint 1, and joint 2 will experience the same torque when the arm is fully extended and loaded.

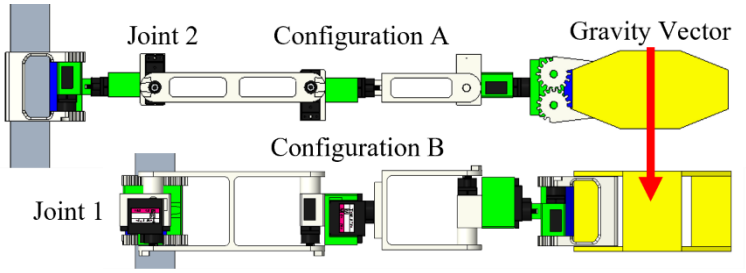


Fig. 7 Maximum loading conditions for joint 1 in configuration B, and 2 in configuration A.

The truss geometry constrains both the minimum and maximum size of the links. The minimum size of the robot is constrained by the need to move vertically on the exterior around the nodes of the truss. Nodes commonly have different geometry from the rest of the strut. The minimum robot link length, L, of the robot is shown in Fig. 8 as

$$L = (r_n + r_g) \tag{1}$$

where r_n is the radius of the node and r_g is the radius of the gripper, both shown in Fig. 8. A robot which can climb over this gap will be able to navigate the rest of the structure. A maximum robot size is heuristically defined as a pair of robots with a payload and a neutral joint pose being able to sit atop a horizontal member without interfering with the diagonal as shown in Fig. 9. Smaller trusses can be navigated, however, the same set of motions may not work to move across the structure requiring modifications to the motions.

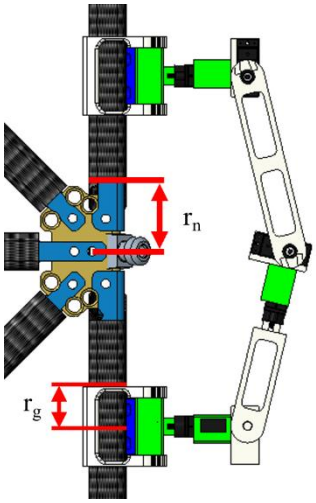


Fig. 8 C2M2 climbing over node, node and gripper radius shown.

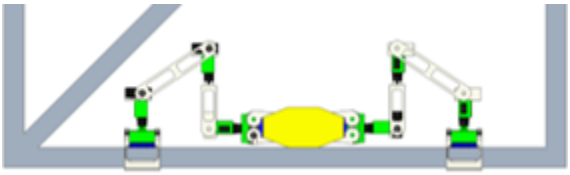


Fig. 9 Demonstration of C2M2s appropriately sized for a truss.

Scaling of the link size was automated by implementation of an algorithm using parameters from the robot and payload. Actuator parameters include width, height, length, and mass and are focused on allowing for selection of an actuator for the application. Payload parameters include the distance between grippers and mass. Utilizing commercial off the shelf (COTS) actuators allows for a lower cost C2M2 system; however, use of COTS component

actuators is limited by what is available from suppliers. The actuator torque and mass are primary drivers of the link length. The scaling algorithm generalizes the size of the robot based on the actuator dimensions and any needed offset between them. A maximum link length is provided as an output. The algorithm finds the torque for a configuration like that shown in Fig. 7 by iteratively increasing the link length of the robot and rerunning the model. When designing for terrestrial gravity, a short link length is typical, especially if electronics are included in the arm due to the forces and moments caused by gravitational force. In reduced gravity applications, the acceptable link length is significantly increased. On the moon, lunar gravity allows for a robot with links six times that of a robot designed for terrestrial gravity. In reduced gravity, a link length shorter than maximum can be selected that maximizes the reach needed for the operations it is designed to perform.

After a configuration has been selected, determination of what payloads are acceptable is useful, hence an algorithm to produce a plot comparing payload mass and CG location was implemented. The output plot is shown in Fig. 10 with the line corresponding to the maximum mass and CG distance from gripper. Inputs are the same as the scaling algorithm but with the link length entered as a constant.

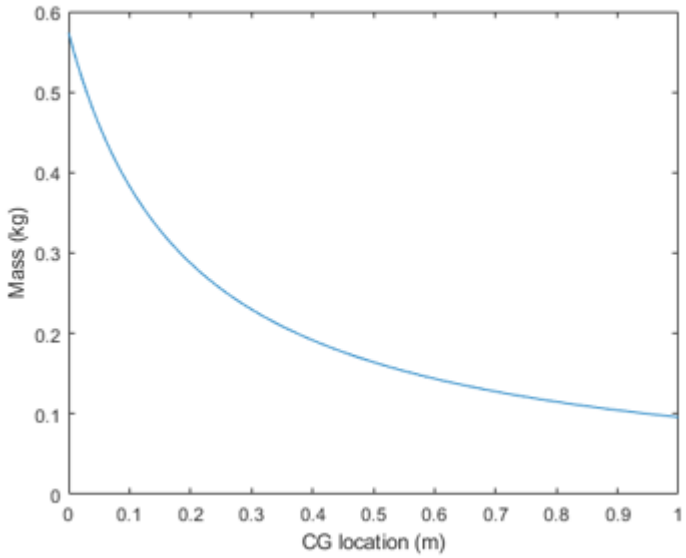


Fig. 10 Line of maximum torque for payload center of gravity vs. mass in lunar gravity, 1.625 m/s^2.

VII. Concluding Remarks

The C2M2 fills the need for a system which can maneuver inside of a truss structure to support the construction, outfitting, and inspection of a structure built on Earth, in orbit, or on a celestial body. The C2M2 also supports the capabilities of the TLT, providing a system which can outfit the structure with additional equipment after construction. The design focuses on internal operations, allowing for traversal through large two- and three-dimensional truss volumes which would be unreachable by a conventional external truss climber. Design of the C2M2 was inspired by numerous other truss climbing and serial manipulator robots. The six DOF configuration improves the payload capacity compared to existing seven DOF systems at the cost of control complexity. Future work will be necessary to determine if there is a significant performance increase by this configuration. The gaits developed here provide a method to validate the capabilities of the robot and a simple set of motions which allow the robot to traverse the structure. The scaling method allows for C2M2s with other actuators to be quickly scaled to a truss structure and validate that the system can operate with the expected payload size and mass. A scale robot was designed using the scaling method developed here and will be built to test the effectiveness. A set of gaits was developed to allow the C2M2 to traverse the TLT both independently and collaboratively. In the future, laboratory tests will demonstrate the operation of the developed gaits on a TLT EDU.

C2M2s are envisioned to operate with numerous robots deployed to support a space infrastructure project collaboratively completing tasks. Tools for the robots will be investigated as a method to allow support of the full construction operation. Tools can either be permanently installed on the robots or delivered as modular upgrades depending on the task. Additionally, control of the C2M2s will need to be investigated and autonomous control software developed to enable assembly using supervised autonomy. Future work will investigate methods to allow

for multiple robots to work together moving a cargo module. Multi robot interaction allows for larger equipment to be moved using the same smaller robots. Control algorithms for teaming robots will be more complex than single and dual robot collaboration, but will provide more versatility in a space application.

References

[1] W. K. Belvin, W. R. Doggett, J. J. Watson, J. T. Dorsey, J. E. Warren, T. C. Jones, E. E. Komendera, T. Mann and L. M. Bowman, "In-space structural assembly: Applications and technology," *3rd AIAA Spacecraft Structures Conference*, San Diego, California, 2016.

[2] W. Doggett, "Robotic assembly of truss structures for space systems and future research plans," *Proceedings, IEEE Aerospace Conference*, Big Sky, Montana, 2002.

[3] W. R. Doggett, J. Heppler, M. K. Mahlin, R. S. Pappa, J. Teter, K. Song, B. White, I. Wong and M. Mikulas, "Towers: Critical initial infrastructure for the Moon," *AIAA SCITECH 2023 Forum*, National Harbor, Maryland, 2023.

[4] W. Doggett, J. Dorsey, B. White, K. Song, L. Simmons, J. Cline, J. Teter, D. Kang, B. Allen, B. Kelley, J. Cooper, I. Wong, W. Waltz, C. Mills, J. Plant, J. Neuhaus, M. Scott, P. Cosgrove, M. Mikulas and R. Neale, "Supervised autonomous assembly to create and evolve persistent assets," *AIAA SCITECH 2022 Forum*, San Diego, California, 2022.

[5] M. L. Grande, R. W. Moses, P. A. Cosgrove, R. P. Mueller, T. J. Prater and A. J. Blanchard, "Protecting crew and surface systems with a long-duration lunar safe haven," *ASCEND 2021*, Las Vegas, Nevada, 2021.

[6] M. M. Mikulas Jr and H. G. Bush, "Design, construction and utilization of a space station assembled from 5-meter erectable struts," NASA TM-89043, 1986.

[7] R. Kumar and R. Hayes, "System requirements and design features of space station remote manipulator system mechanisms," *JPL, The 25th Aerospace Mechanisms Symposium*, Pasadena, California, 1991.

[8] Y. Yoon and D. Rus, "Shady3D: A robot that climbs 3D trusses," *Proceedings 2007 IEEE International Conference on Robotics and Automation*, Rome, Italy, 2007.

[9] B. Jenett and K. Cheung, "Bill-e: Robotic platform for locomotion and manipulation of lightweight space structures," *25th AIAA/AHS Adaptive Structures Conference*, Grapevine, Texas, 2017.

[10] Y. Xu, B. Brown, S. Aoki and T. Yoshida, "A Space Station robot walker and its shared control software," *Conference on Intelligent Robots in Factory, Field, Space, and Service*, Houston,Texas, 1994.

[11] S. Leder, R. Weber, D. Wood, O. Bucklin and A. Menges, "Distributed robotic timber construction," *Proceedings of the 39th ACADIA*, 2019.

[12] T. Zhu, G. I. Fernandez, C. Togashi, Y. Liu and D. Hong, "Feasibility study of LIMMS, a multi-agent modular robotic delivery system with various locomotion and manipulation modes," *2022 19th International Conference on Ubiquitous Robots (UR)*, Jeju, Republic of Korea, 2022.

[13] A. Chin, R. Coelho, L. Brooks, R. Nugent and J. Puig-Suari, "Standardization promotes flexibility: A review of CubeSats' success," *6th Responsive Space Conference*, Los Angeles, California, 2008.

[14] J. Dorsey, T. Jones, W. Doggett, B. King, C. Mercer, J. Brady, F. Berry, E. Anderson and G. Ganoe, "Recent Developments in the design, capabilities and autonomous operations of a lightweight surface manipulation system and test-bed," *AIAA SPACE 2011 Conference & Exposition*, Long Beach, California, 2011.