Verification and Validation of a Conceptual Model of the Auto-Rigging Payload Handling and Off-Loading System Using LEGO Technic System and Three-Dimensional Printed Parts

Kyongchan Song,[1] Brace White,[1] Iok Wong[1]
NASA Langley Research Center, Hampton, VA 23681

A conceptual model (CM) can be used to validate a concept in modeling and simulation life cycles. During the 2020-2022 Coronavirus disease 2019 (COVID-19) pandemic, for employee safety NASA implemented center closures and mandatory telework for the entire workforce. During this challenging time, engineers and researchers at NASA Langley Research Center (LaRC) looked for safe and innovative approaches and methods to continue the development of CMs for various projects. Engineers and researchers at LaRC researched Auto-Rigging Payload Handling and Off-Loading System (ARPHOLS) for payload handing and off-loading a system on an inclined lunar lander deck. In this paper, the development of a CM and the verification and validation of a conceptual idea for ARPHOLS using a LEGO Technic system and three-dimensional printed parts is presented.

I. Introduction

For concept development and model design, a conceptual model (CM) can be used to validate the proposed design. The CM can be defined as "an abstract representation of something generalized from particular instances" [1]. There are many different perspectives and applications of CMs including software [1,2,3], non-software specific descriptions of the simulation model [4], business models [5], and a device composed of basic machine elements such as gears, bearings, fasteners, springs, seals, and couplings. As the CM is developed based on the design requirements for the given mission, a comprehensive and detailed validation of the CM is needed in early model development phase. In this paper, the CM of the Auto-Rigging Payload Handling and Off-Loading System (ARPHOLS) is presented along with a discussion of the validated demonstration of the prototype CM.

In March 2020, because of the Coronavirus disease 2019 (COVID-19) pandemic, NASA faced unprecedented challenges due to center and facility closures, and the shift to a mandatory telework posture for much of its workforce. This resulted in disruptions to staff availability, materials and supply chains, and program and project timetables. The center closures lasted almost two years until the second half of 2022. During the center closure period, mandatory telework, and limited resources impelled engineers and researchers at NASA Langley Research Center (LaRC) to look for innovative and cost-effective research methods while maintaining workforce safety during the pandemic. One of the research subjects during that time was to develop a payload handling and off-loading system [6]. A lunar lander can land on the Moon's surface with an incline of up to 15 degrees but using an autonomous lunar crane like the Lightweight Surface Manipulation System (LSMS) [8] to lift payloads off an inclined lander deck could be problematic without spotters to stabilize swinging and manipulate orientation. The ARPHOLS was proposed to limit swinging while allowing for control of the payload orientation during the lifting process. For this research effort, payload orientation control algorithms of ARPHOLS were developed [6] and computer aided design (CAD) models were developed for the three-dimensional (3D) representation of ARPHOLS. Subsequently, a physical CM was

[1] Research Aerospace Engineer, Structural Mechanics and Concepts Branch, Mail Stop 190, AIAA Member.

constructed to validate the mechanism concept in the laboratory. Since resources and lab space were limited during the COVID-19 pandemic, the CM of ARPHOLS was developed using the LEGO* Technic system and 3D printed parts and the CM mechanism was validated off site.

The focus of this paper is to present the development and validation of a payload handling and offloading CM using a LEGO* Technic system and customized 3D printed parts during the COVID-19 pandemic. First, the LEGO* Technic system is introduced in Section II. Details of the CAD model and CM of the ARPHOLS are presented, and validation of the CM is discussed in Section III. A science, technology, engineering, and mathematics (STEM) outreach activity using the LEGO* LSMS and other space structures is discussed in Section IV. Lastly, concluding remarks are given in Section V.

II. LEGO Technic System

LEGO* Technic system* [9] is a line of LEGO* interconnecting plastic rods and mechanical components, such as motors, gears, pneumatics, and pulleys. With a LEGO* robotic controller and supporting program package, the LEGO* Technic system can be used to create models with more complex technical functions than traditional static brick-based models. An example of a LEGO* Technic system is shown in Fig. 1. There are many user groups and nonprofit organizations utilizing LEGO* Technic systems for personal hobby and STEM activities. For Inspiration and Recognition of Science and Technology (FIRST) LEGO* League is a good example of how LEGO* Technic system can be used for STEM activities to develop various types of machines and robots. An example of a robot used in a FIRST LEGO League competition is shown in Fig. 2.

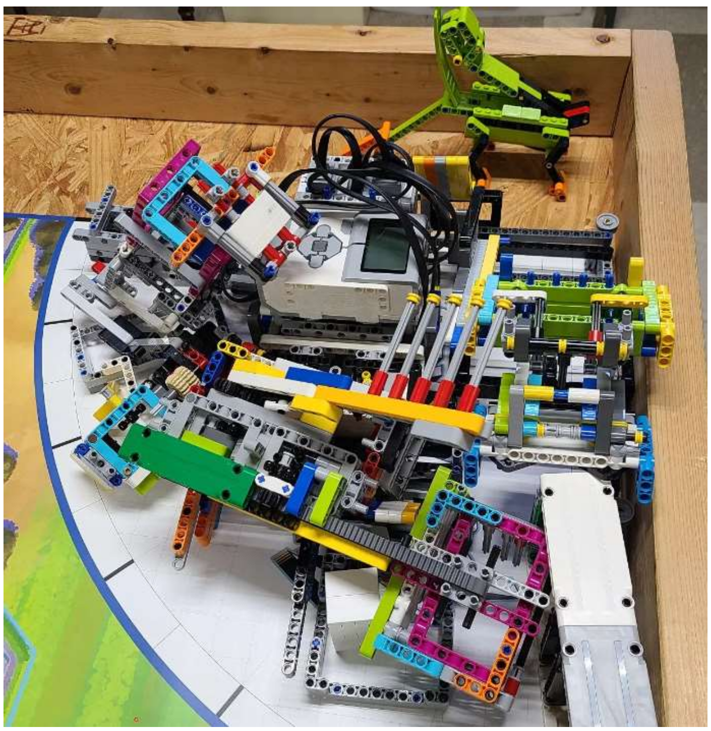

Figure 1. LEGO* Technic System Example (LEGO* Education EV3 Set).

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Figure 2. An example of a LEGO* robot used in a FIRST Lego League competition.

III. Auto-Rigging Payload Handling and Off-Loading System Loading System (ARPHOLS)

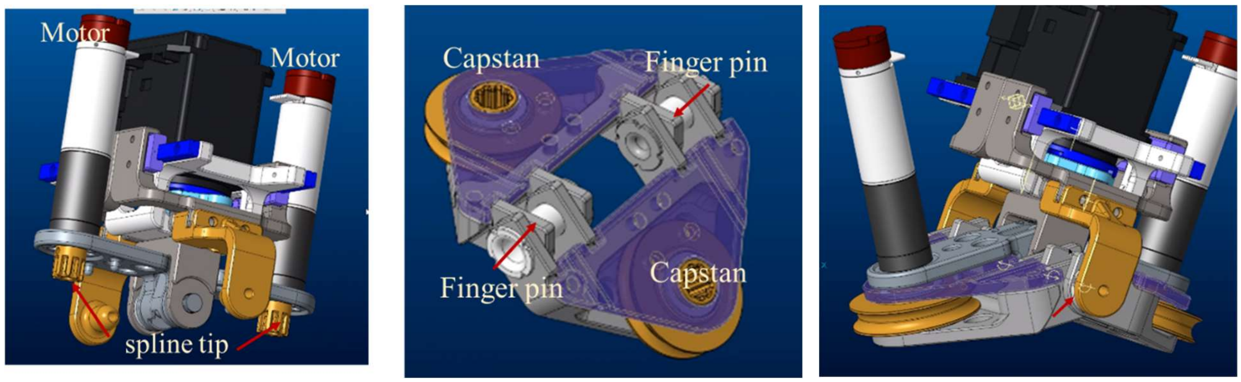
One of the design requirements of a lunar lander is that it can safely land on a surface that has an incline of up to 15 degrees [7]. However, using an autonomous lunar crane, such as the LSMS [8], to lift payloads from an inclined lander deck could pose challenges. On Earth, cranes typically require spotters to stabilize swinging and adjust the orientation of lifted objects. Without watching the lift, lifting a payload from an inclined lunar lander deck could be difficult to manage and could cause damage to payload, the lander, and the crane. To address this issue, ARPHOLS was proposed as a mechanism to minimize swinging and manipulate the payload orientation.

A. Conceptual Model of ARPHOLS

The objective of ARPHOLS is to make rigging a payload as robotically simple as possible. ARPHOLS is based on a capstan-cable-driven system (CCDS) for auto-rigging, and a post-rigging adjustment system to allow the operator to adjust the lifting angle to level or tilt the payload to achieve the desired position and match the targeted destination. A CCDS has four major components: two capstans, the capstan joint gripper, the motor-mounting joint, and two motors.

- The capstan joint gripper houses the capstans and has a pair of motor-actuated parallel gripping finger pins that will lock onto the motor-mounting joint after the mounting joint motors are engaged.
- The motor-mounting joint is attached to the two motors and can be rotated on the same axis as the capstan joint gripper. The mounting joint has a torsion spring to keep the joint open prior to engagement.
- The two motors mounted to the motor-mounting joint each have a spline tip with tapered teeth matching the spline slot found on the capstans, then two motors can spin capstans independently.

The CAD model of the CCDS is shown in Fig. 3.



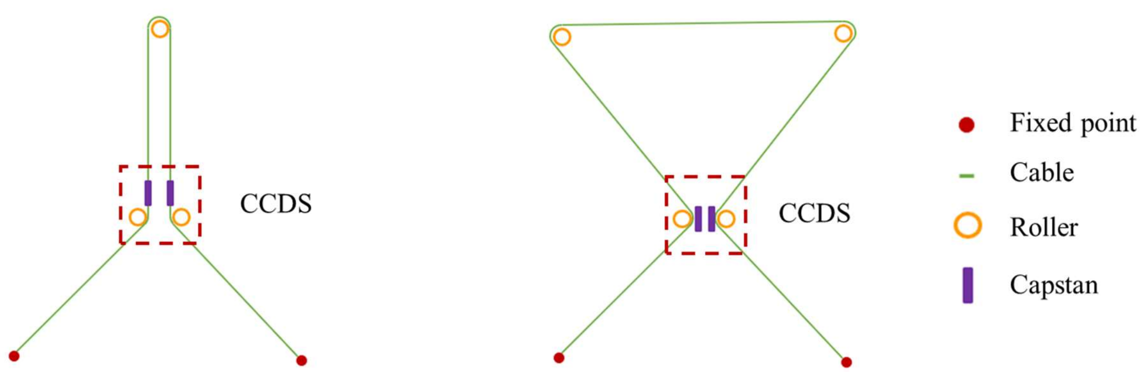
(a) Motor-mounting joint

(b) Capstan joint gripper

(c) Attached mounting joint and capstan joint gripper

Figure 3. Component of the CCDS in CAD models.

A single cable is routed through the CCDS, and a series of rollers attached to the payload are used to achieve the rotational control for orientating the payload. Two different attachment options to the payload are available: a three-point attachment with two-degrees-of-freedom (2-DoF) of rotational control for triangular or circular volumetric payloads and a four-point attachment with 2-DoF of rotational control for most other volumetric payloads. The three- and four-point attachment options are shown in Fig 4. The ultimate vision for ARPHOLS is a fully automated system, which can sense the incline angle of the lander deck, adjust the cable section lengths to match that angle, pick up and move the payload to the desired offload location without it swinging, adjust the orientation of the payload to match the location incline, and safely offload the payload. In order to achieve such automation, payload orientation control algorithms were developed. A detailed control formulation of the ARPHOLS system is provided in Ref. [7].



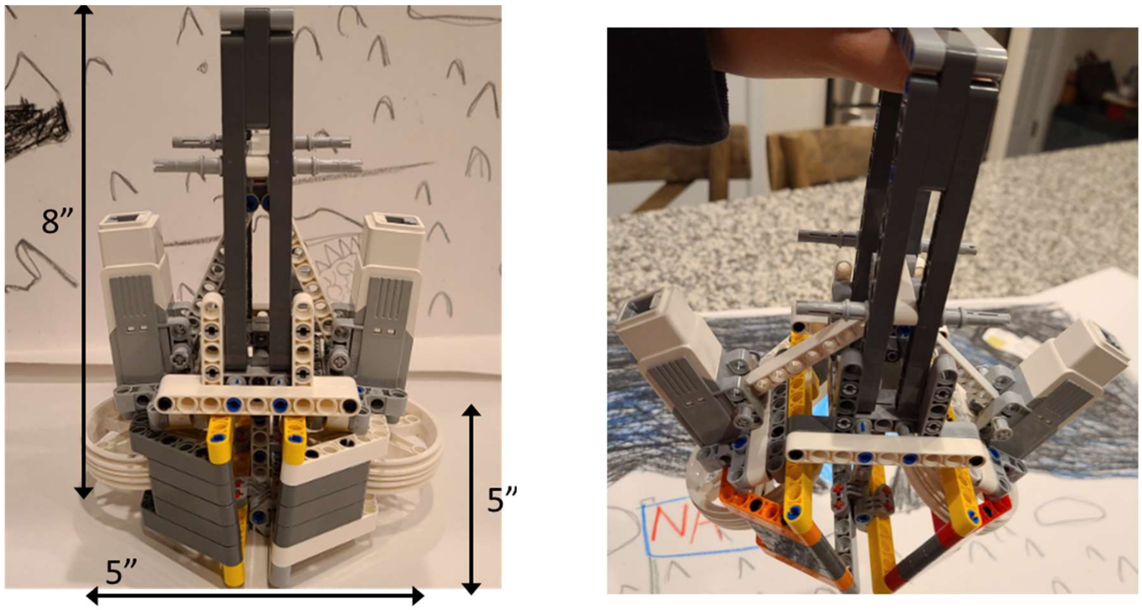
(a) Three-point cable attachment system

(b) Four-point cable attachment system

Figure 4. (a) Three- and (b) four-point cable attachment system.

B. Verification and Validation of the LEGO[*] CM

The CM model of the CCDS was developed utilizing a LEGO[*] Technic system. The objectives of the CM were to verify the mechanisms of the CCDS, such as the hinge, and to validate the three- and four-point single-cable leveling control system. The hinge inside the capstan joint gripper and the motor-mounting joint allows the capstans to auto-match the tension vector of the cable segments without the need for powered actuation. The LEGO[*] CM was able to move the hinge to the open and closed positions of the CCDS, thereby verifying the mechanical capability as shown in Fig. 5.



(a) Closed position (b) Open position

Figure 5. CCDS position for different payload tension vectors.

The LEGO[*] CM of the CCDS was attached to a beam (representing the arm of the LSMS) and either a three- or four-point single cable attachment system linked the LEGO[*] CM to a dummy payload to demonstrate lifting and offloading using the ARPHOLS, as shown in Fig. 6. One operator controlled the end of the beam to move and lift the ARPHOLS, and another operator controlled the CM with the LEGO[*] Technic controller which was connected to a laptop via Bluetooth. Then, the single cable leveling control system was validated in the home garage.

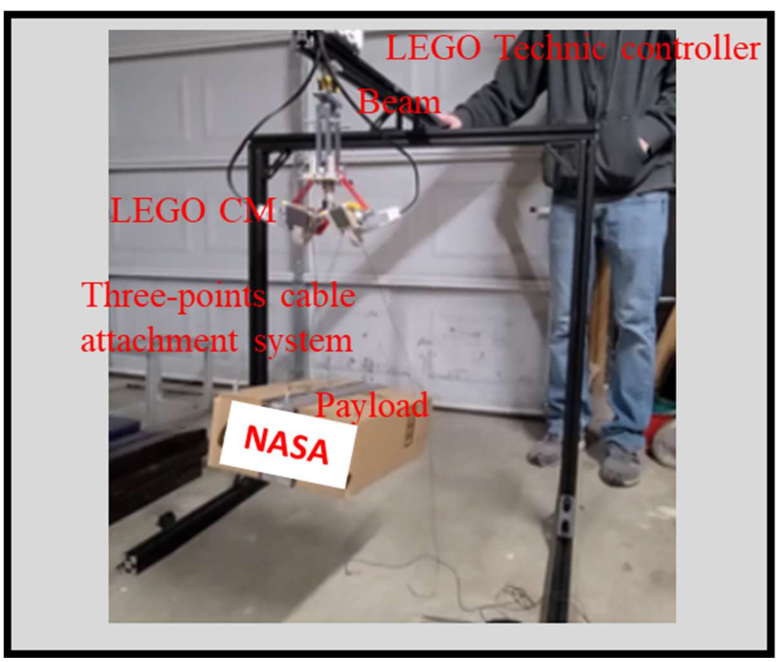


Figure 6. Validation of single cable leveling control system.

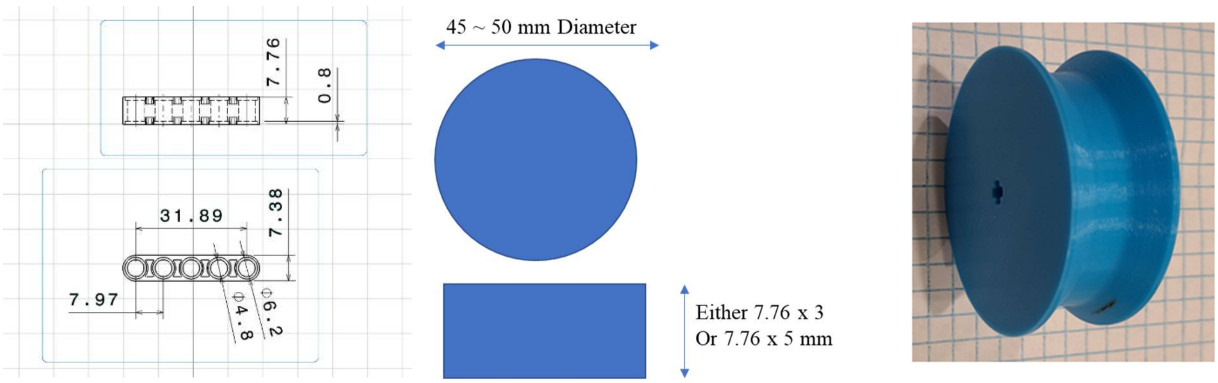
The concept was successfully validated with the single-cable attachment system with the CM for the following objectives:

- Prevent the payloads from swinging when lifting them from the surface with a slope of up to 15 degrees.

- Adjust the payload's orientation to be placed on a different slope.
- Ability to rotate the payload upside-down if needed.

However, the LEGO* capstan part did not provide smooth cable management and the capstan with 3D custom design was needed to accomplish better cable management.

Several capstan profiles were reviewed, and capstans were fabricated using a 3D printer for the CM. The profile of the capstan was designed based on the size of the selected cable, and how many wraps the cable would have on the capstan to determine the sectional geometry of LEGO* Technics pieces. There are guiding features on each side of the capstan to keep the cable in place and guide the cable toward to the center of the capstan as they are reeling in and out of the capstan. Geometry of LEGO* Technic pieces to hold the capstan, as well as the dimensional requirements for the capstan, and the final fabricated capstan are shown in Fig. 7.



(a) LEGO* pieces dimension (b) Capstan geometry requirement (c) Final 3D printed capstan

Figure 7. Capstan requirement and final 3D printed capstan.

The CM model of the CCDS was modified for custom 3D printed capstans. Because the original hinge mechanism to the open and closed positions could not be accurately modeled with LEGO*, the CM of the CCDS was simplified by removing the hinge mechanism concept and modified motor orientation. The final version of the CM model of the CCDS is shown in Fig. 8.

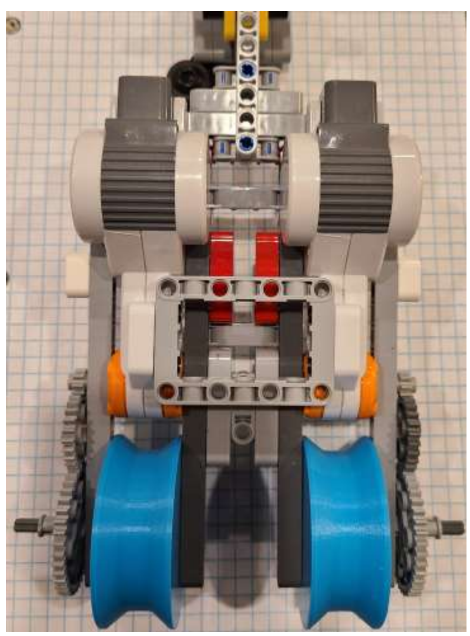


Figure 8. The simplified CM model of the CCDS.

The modified LEGO* CM of the CCDS was attached to either a three- or four-point single cable attachment system linking the LEGO* CM to a dummy payload to demonstrate lifting and offloading using the ARPHOLS, as shown in Fig. 9.

The modified LEGO* CM of the CCDS successfully validated the ARPHOLS system and provided smoother cable management with a simpler mechanism compared to the initial CM. Additionally, the validation study of the ARPHOLS system provided insights into the CCDS mechanism and suggested that a simplified concept without the hinge could be a valuable option for future CCDS development.

(a) Three-point cable attachment system (b) Four-point cable attachment system

Figure 9. Validation of modified single cable (a) three-point and (b) four-point leveling control system.

IV. Outreach Activity

After LaRC reopened for normal operations in 2022, other LEGO* CMs of in-space assembly projects at NASA LaRC were developed for the public display and outreach events. LEGO* LSMS and Tall Lunar Tower (TLT) [9] models were displayed with presentation posters at various project meetings and public events. In Fig.10, the display is shown of LEGO* LSMS and TLT models at the In-Space Servicing, Assembly and Manufacturing Technology Transfer Day Workshop in October 2022. The display of LEGO* LSMS and TLT models at LaRC Open House in October 2023 is shown in Fig 11. The LEGO* models displayed alongside the presentation posters brought more interest and positive feedback from the attendees than the presentation posters alone. Public interaction with the LEGO* models at the various STEM outreach events was very helpful for explaining the systems and was especially effective among elementary and middle school students.

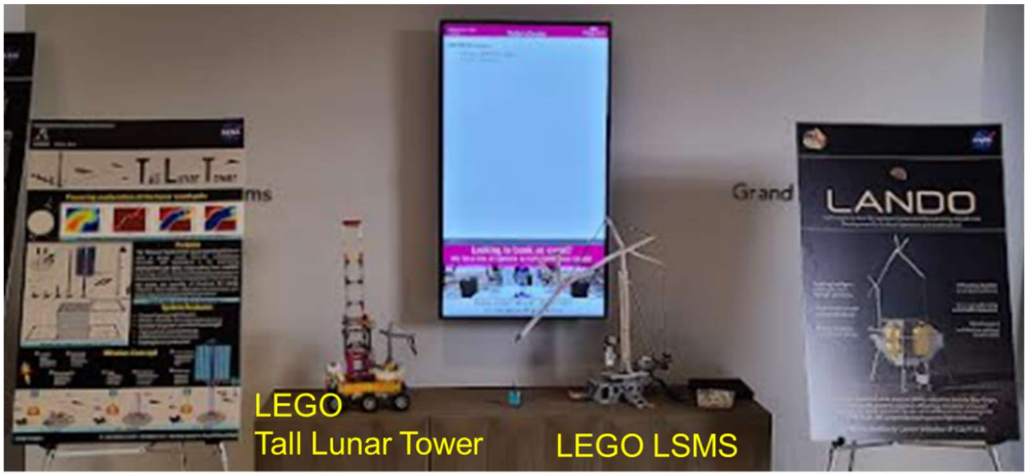


Figure 10. Display of LEGO* LSMS and TLT models at in-space servicing, assembly and manufacturing technology transfer day workshop in October 2022.

Figure 11. Display of LEGO* LSMS and TLT models at NASA LaRC Open house in October 2023 [10].

V. Concluding Remarks

During the early model design phase, exploring various modeling approaches for a given problem using initial concepts is essential to validate the proposed concept. NASA faced unprecedented challenges during the COVID-19 pandemic due to limited access to onsite resources. As engineers continued to research various projects, LEGO* and 3D printed parts provided cost-effective and efficient tools for the development of CMs that could be leveraged for telework based projects.

The development and validation of CM of ARPHOLS is discussed in this paper demonstrating that incubating, developing, and validating a new concept can be achieved using the LEGO* technique system during the early model design phase. Validation of the cable rotational control of the ARPHOLS system for payload lifting and off-loading indicated that LEGO* and 3D printed parts can be useful tools for developing engineering concepts. In addition, dynamic LEGO* models of space structures can be effective outreach tools for STEM events.

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