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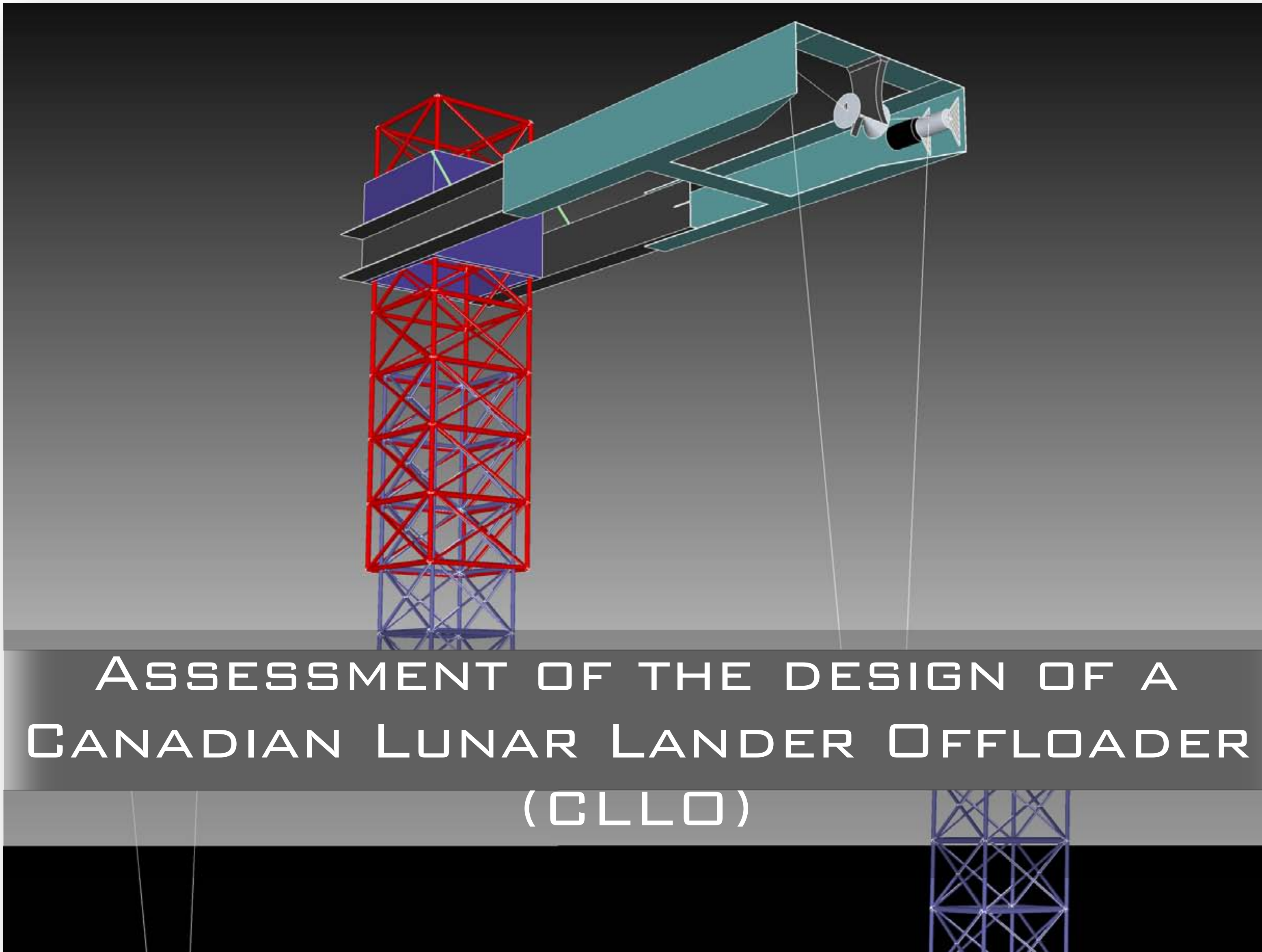

ASSESSMENT OF THE DESIGN OF A CANADIAN LUNAR LANDER OFFLOADER (CLLO)

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Summary

This report describes and assesses the design of a robotic system that offloads planetary rovers and auxiliary payloads from a lunar lander onto the lunar surface or other waiting rovers. Specifically the report addresses the structural and kinematic challenges of the Canadian Lunar Lander Offloader (CLLO) design, and their adherence to a set of system requirements defined by NASA and the Canadian Space Agency.

CLLO is capable of five axes of motion, and can be defined as a hybrid forklift-crane system. The crane assembly is mounted at the end of telescopic forks, which are themselves mounted on a telescopic tower and turntable. The entire system begins collapsed and stowed on the lander deck during launch, and is deployed on the deck to offload lunar rovers to the moon's surface using its crane and cable assembly. It can also detach itself from the lander deck and reposition itself on a waiting lunar rover in order to offload palletized auxiliary payloads. The system has been designed to safely offload up to 6000kg of cargo up to a tilt of 12 degrees from horizontal.

It is concluded that the CLLO is not optimized for any one single task, but fulfills the system requirements and is a good compromise between versatility, accuracy and reliability.

It is recommended that more detailed design and prototyping activities be completed in order to further the development of the concept. It is also recommended that the auxiliary

payloads be more clearly defined, and that studies be conducted to examine additional uses of the system beyond simple offloading of the lunar lander.

1. Introduction

The plan to return man to the Moon began in 2004 with the announcement of the Vision for Space Exploration (or Constellation program) by U.S. President George W. Bush[3]. Touted as the successor of the Apollo missions conducted in the 1960's and 1970's, the program mixes new technology and tried and tested mission planning to return humans to the moon by 2020[1]. Although commonly seen as a repeat of the Apollo missions, the Constellation program shifts the focus from exploration-type sortie missions to infrastructure building missions, whose ultimate goal is to develop the technologies and processes needed to sustain humans on distant planets for long periods of time [1]. One of the most critical elements of the Constellation program is the Altair lander, whose existence allows for the safe transport of cargo and personnel to the lunar surface. Although well suited for its purpose of transport, the Altair lander is not capable by itself of lowering any cargo atop its deck to the lunar surface or to a waiting rover. As such, two systems are used to offload cargo from the lander. The first –the Jet Propulsion Laboratory's All-Terrain-Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robot - is being designed to offload large Habitat Modules[1]. The second –a system identified in this report as the Canadian Lunar Lander Offloader (CLLO)- is being designed by MDA Space Missions to offload NASA's Lunar Electric Rovers or any other smaller payloads.

1.1. Report objective and layout

The objective of this report is to describe and assess the design of the CLLO, specifically on its adherence to the system requirements provided by NASA and the kinematic and structural feasibility of the design. The report does not show the calculations performed for structural analysis or power consumption. It is organized into four major sections: System requirements, Design Overview, Kinematic/Structural Assessment, and Conclusion and Recommendations. System requirements provides the main requirements and restrictions the CLLO system has to comply with, as directed by NASA and CSA. Design Overview briefly summarizes the design and explains the operation of the CLLO. Kinematic/Structural Assessment focuses on each component of the design and describes what alternatives were explored and why the chosen design is optimal. Conclusion and Recommendations describes what lessons were learned from the design process of the CLLO and what steps should be taken to further its development.

2. System Requirements

The following table outlines the system requirements for the Canadian Lunar Lander Offloader (CLLO) according to the National Aeronaturics and Space Administration (NASA) and the Canadian Space Agency (CSA). Only the requirements relevant to this report are shown.

Category	Requirement
System Mass	Must have a mass of 500 kg or less
Payload Handling	-Must be capable of lifting the 6000 kg Lunar rovers off the lander and onto the lunar surface (see image below)  **Figure 1: Lunar Rover position on Altair lander [source: NASA document]** -Must be capable of offloading smaller auxiliary payloads located on the unused portions of the lander deck and offload them onto nearby flatbed type rovers , with an accuracy of +/- 5cm
Stowage	-Must have a minimal footprint on the lander, and stow in the highlighted areas of the lander deck (see below images)

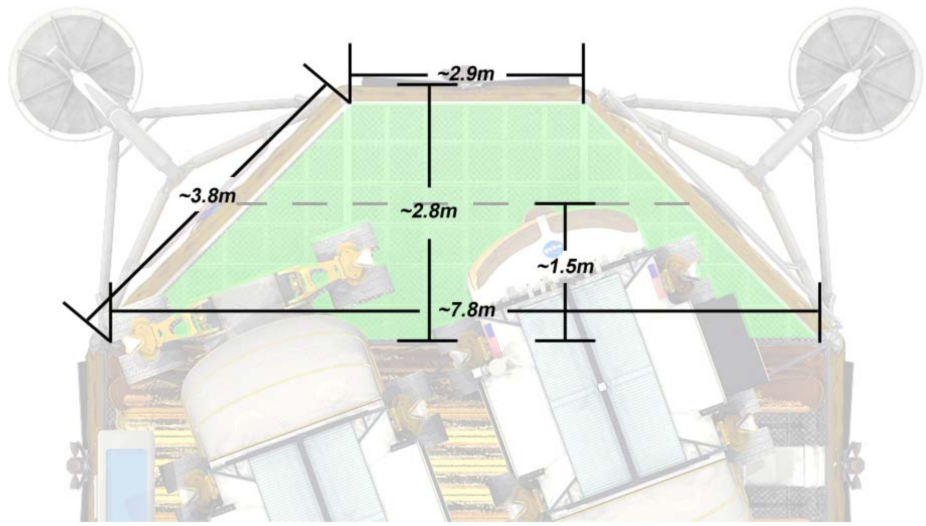


Figure 2: Dimensions of stowable area (planar view) [source: NASA document]

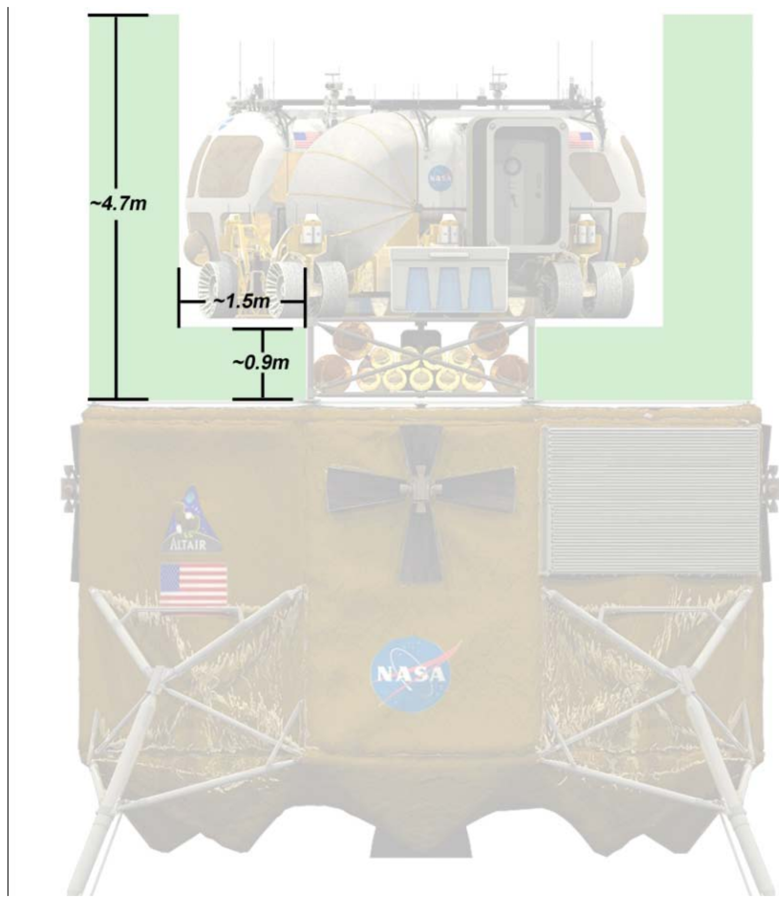


Figure 3: Dimensions of stowable area (profile view) [source: NASA document]

-Must not interfere with the design or layout of other structures on the lander, nor can it hang over the edge of the lander

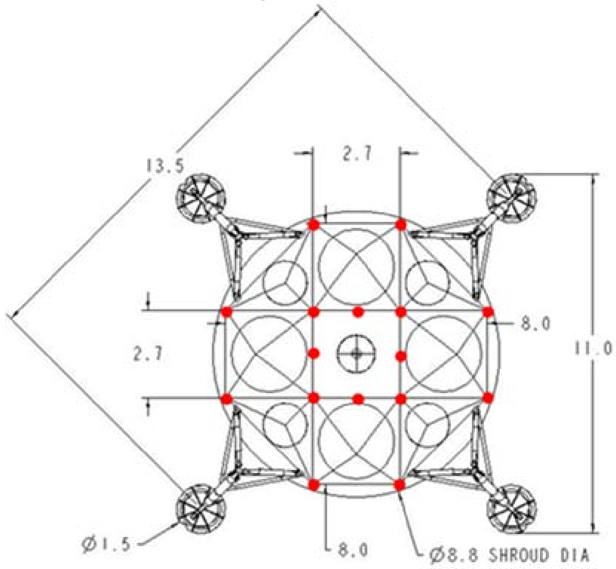
Deployment	-Must be capable of repositioning itself from the lander deck to a nearby flatbed type rover without the intervention of astronauts or other robotic systems -Must be secured to the lander through hardpoints found on the perimeter of the octagonal deck (see red dots located on image below)  **Figure 4: Altair lander deck hardpoints** -footprint when deployed should be no greater than 1 square meter (1 by 1 meter)
Uneven Terrain	-Must be capable of offloading lunar rovers to lunar surface when the lander deck is sloped up to 12 degrees from the horizontal
Autonomy	-Must be capable of being teleoperated, with no astronaut in the vinicity

Table 1: CLLO System Requirements

3. System Overview

The following section summarizes the design of Canadian Lunar Lander Offloader, and is divided into two parts: System components and Sequence of Operations. System components outlines the overall design of the CLLO, while Sequence of Operations illustrates where the system is to be positioned on the lander during launch, and how it is deployed to offload the lunar rovers and auxiliary payloads.

3.1. System Components

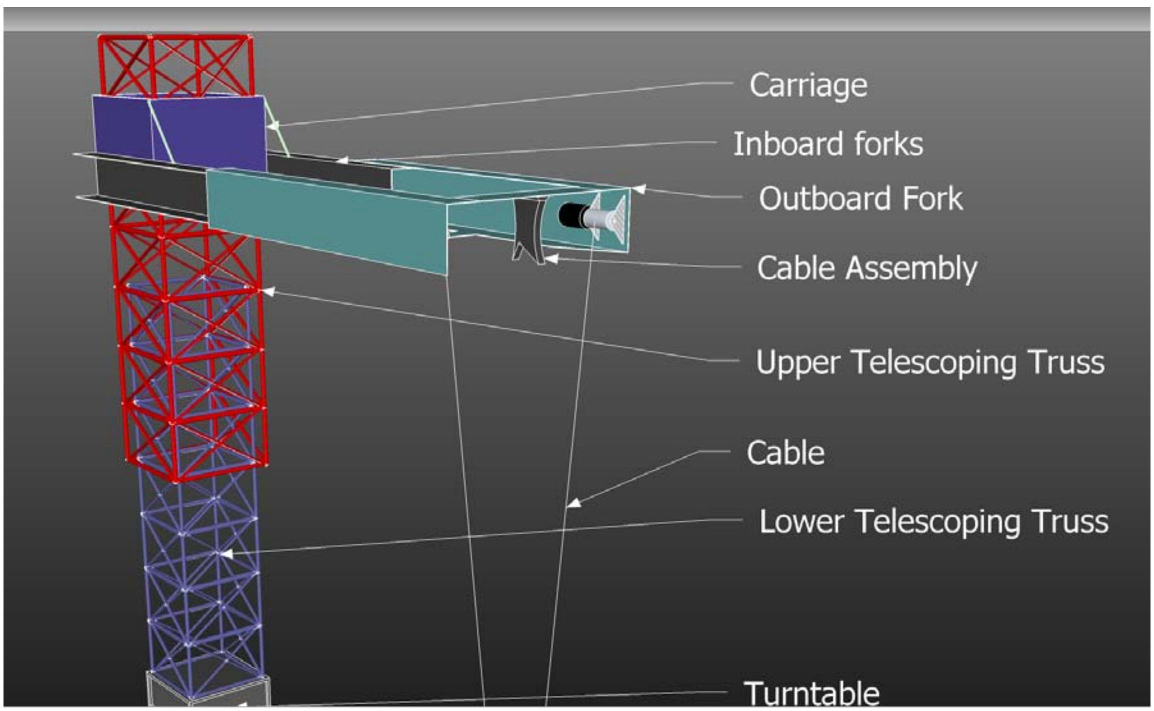


Figure 5: CLLO System Components

As seen in Figure 5, the CLLO concept can be described as a hybrid between a crane and a forklift. The system features five axes of movement:

1. Turntable which allows the entire system and the attach payload to rotate 360 degrees
2. Telescopic tower which allows the height of the system to be modified in order to transition from a stowed to deployed configuration
3. Carriage capable of translational motion up and down the upper telescoping truss allowing for increased versatility
4. Outboard fork capable of extending and retracting into inboard forks to facilitate stowage, redeployment and auxiliary payload manipulation
5. Crane assembly which allows payloads attached to the cable to be vertically translated by retracting or extending the length of exposed cable

The five motion axes can be combined in various combinations to manipulate the positions of payloads on the Altair lander and offload them onto waiting rovers or onto the lunar surface. Figure 6 is a scale diagram showing the dimensions of CLLO in a more orthographic projection. It should be noted that the Outboard fork is in fact one structure, with two longitudinal pieces being spanned by two crossbeams.

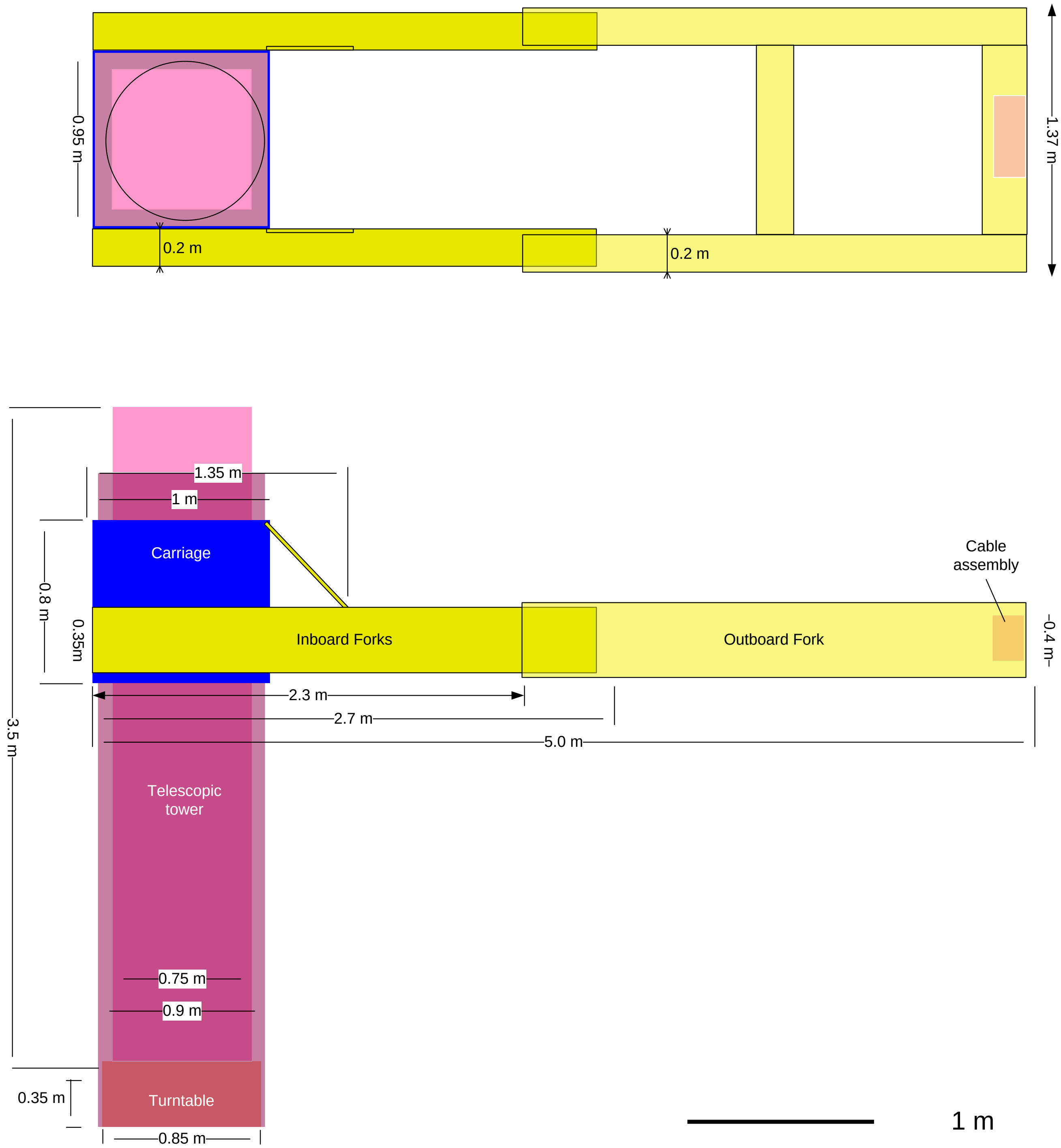


Figure 6: Dimensioned CLLO diagram

3.2. Sequence of operations

3.2.1. Stowed configuration

The following scale diagram illustrates the layout and dimensions of the stowed configuration of CLLO. This configuration will be used during launch of the lander. It should be noted that the forks are stowed collapsed into one another, and that the Upper telescoping truss is capable of stowing overtop the turntable structure in order to place the forks in contact with the lander deck.

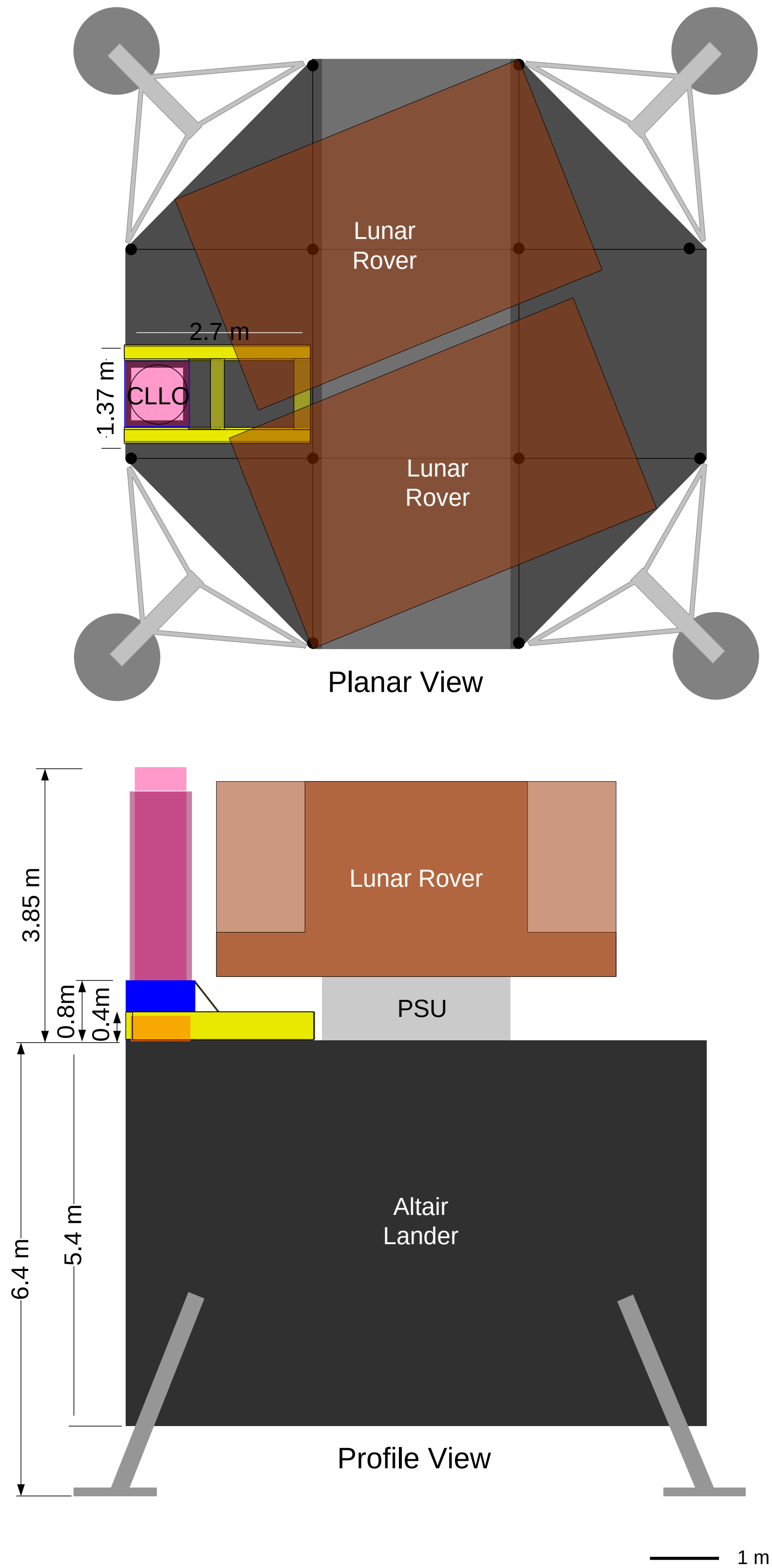


Figure 7: Lander mounted CLLO stowed configuration

3.2.2. Offloading Lunar Rover

The following scale diagram illustrates the steps performed by CLLO in order to capture and offload the lunar rovers positioned on the Altair lander. It should be noted that the forks in this configuration act as crane booms, supporting the cable assembly as it mates with the lunar rover and offloads it over the side of the lander. It should also be noted that the profile view of the lunar rovers has been illustrated to show their maximum size due to a skewed orientation (ie. Rover aligned diagonally with respect to CLLO).

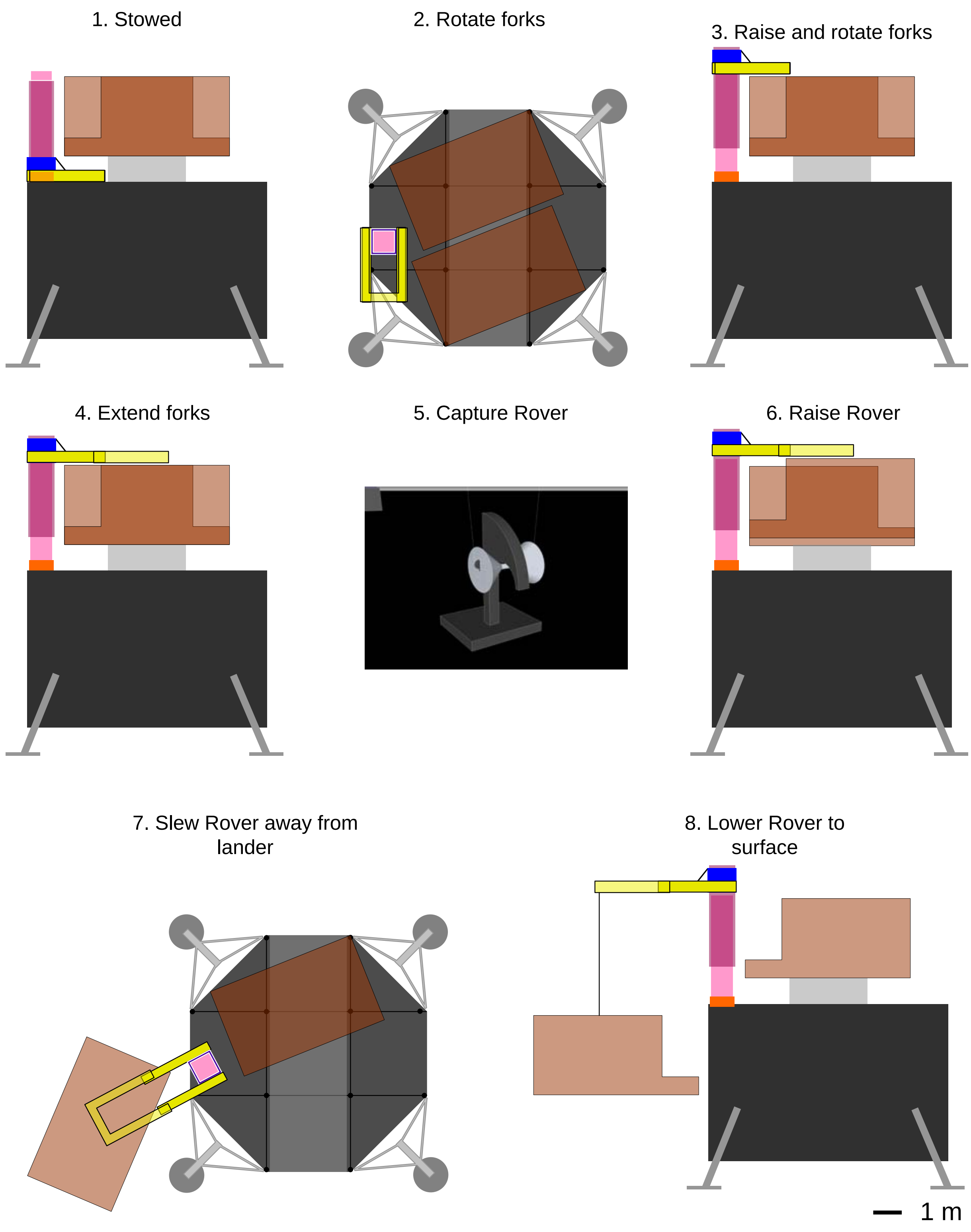


Figure 8: Operation sequence for offloading lunar rover

3.2.3. Offloading Auxiliary Payload

The following scale diagram illustrates the steps performed by CLLO when repositioning onto a waiting lunar rover and offloading a cargo pallet holding auxiliary cargo (specifics of the auxiliary cargo are not defined). It should be noted that a different configuration of the Altair lander has been illustrated, with a single large lunar Habitat Module being centrally positioned on the deck instead of two separate lunar rovers. This configuration was depicted as it illustrates the most probable scenario in which auxiliary cargo will be found, and because it shows the largest possible sized pallet that can fit on the lander deck.

It should also be noted that the CLLO system is capable of detaching itself from the lander deck in order to reposition itself onto a waiting lunar rover. This unique capability fulfills the system requirements of repositioning -defined earlier in the report, and allows CLLO to be used beyond the environment of the lunar lander for payload manipulation.

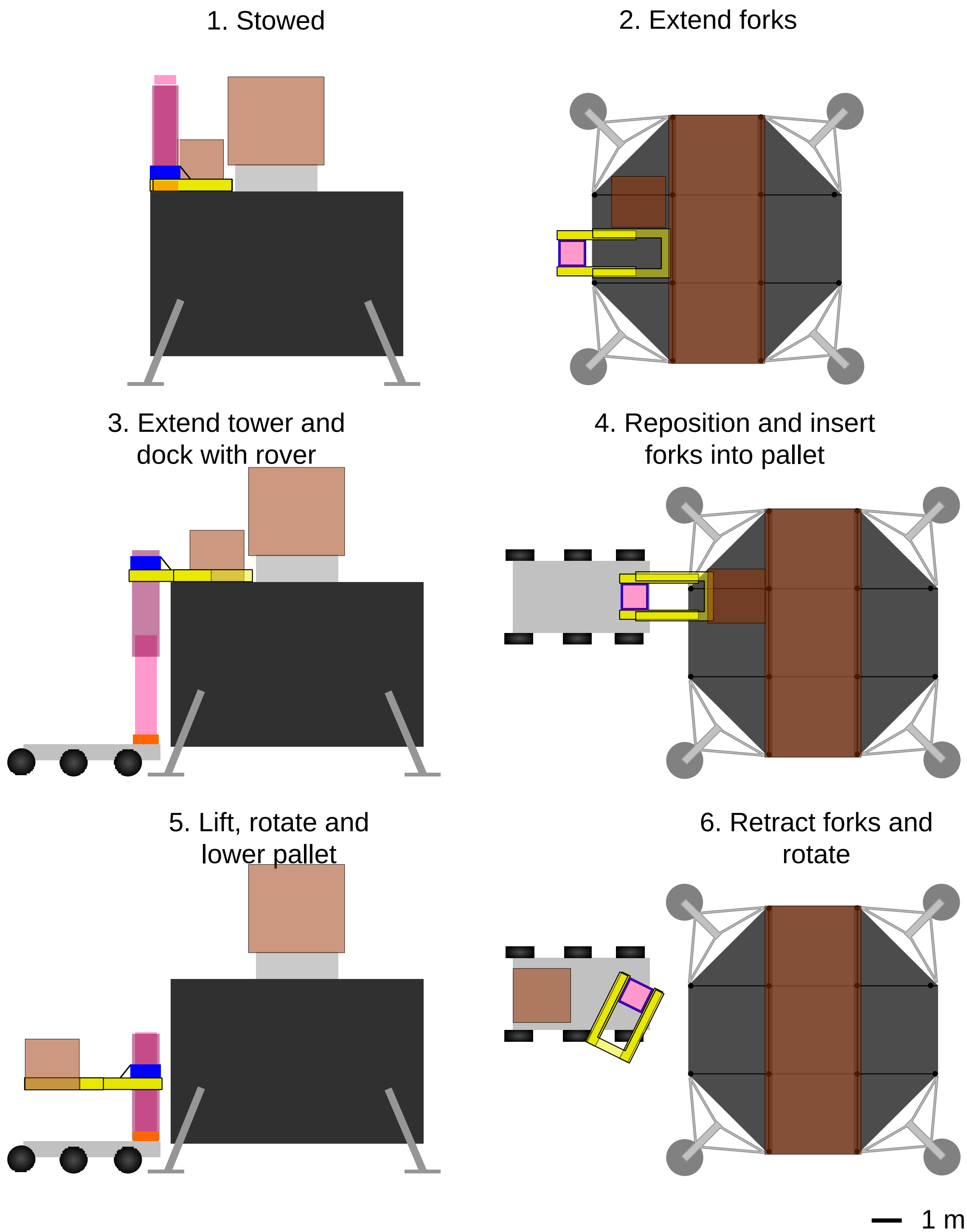


Figure 9: Operation Sequence for CLLO repositioning and auxiliary cargo offloading

4. Kinematic/Structural Assessment

The following section describes the design of each component of CLLO, outlining the alternatives presented and why the given design is optimal. This section also describes the kinematic assessments performed to show that CLLO is capable of offloading the lunar rovers at a 12 degree slope with respect ot the horizontal.

4.1. Forklift Hybrid Concept

The CLLO is unique in that in combines both a forklift and a crane system in order to manipulate payloads positioned on the lunar lander deck. Three alternatives were also studied, and the design trade-off can be found in the following table:

Design	Characteristics	Advantages	Disadvantages
Crane System	-uses a series of cables and booms to pick up, manipulate and offload lander payloads -cable features an end effector in order to capture payloads	-lightweight, low power consumption -lowest mechanical complexity and number of actuators -does not need to reposition itself to lower payloads to the surface	-tendency for cable to align with gravity vector means increased lateral misalignment -oscillations in the cable due to inertia (ie. Pendulum motion) makes fine positioning and payload capture difficult
Forklift	-uses one-two forks to grasp the payload/rover -mounted on a tower to allow forklift to raise and lower payload captured on the fork structures	-high level of accuracy, minimal misalignment -relatively low complexity with few joints	-orientation of lunar rovers makes it difficult to capture -offloading of rovers would be very difficult without a partner lunar rover already on the surface, as the base of the forklift will have to be deployed over the edge of the deck, and span the entire height of the lander
Deployable Ramp	-ramp unfolds from stowed position beside the lunar rovers in order to form an angled	-allows lunar rovers to simply drive themselves off the lander -once deployed, no further	-complex deployment mechanism and very large footprint -cannot be redeployed onto a

	platform from the lander to the lunar surface	power needed (passive design)	rover -cannot unload auxiliary payloads by itself
Forklift Hybrid	-combines forklift and crane system, using a crane cable to lower rovers to the lunar surface and a forklift system to offload auxiliary payloads	-versatile, capable of being repositioned onto rover without loss of functionality - provides accuracy of forklift and wide reach of crane system -small footprint, easy deployment	-large number of actuators and complex

Table 2: System Concept design trade-off

As seen from Table 2, The Forklift Hyrbid provides the best balance between payload positioning accuracy and system flexibility, and will be used as CCLO's baseline concept. Its multiple actuators and axes of movement increase the mass and complexity, but the positioning and stowage benefits it provides outweigh the potential drawbacks.

4.2. Fork Design

4.2.1. Forklift Tine cross section

There are a number of unique features that can be found when observing the fork structure of the CLLO. The most visible feature is the depth of the forks, which are 40 cm deep, much deeper than the forks found on terrestrial forklifts in industrial warehouses. There are two reasons for this: mass/load moments and actuator volume.

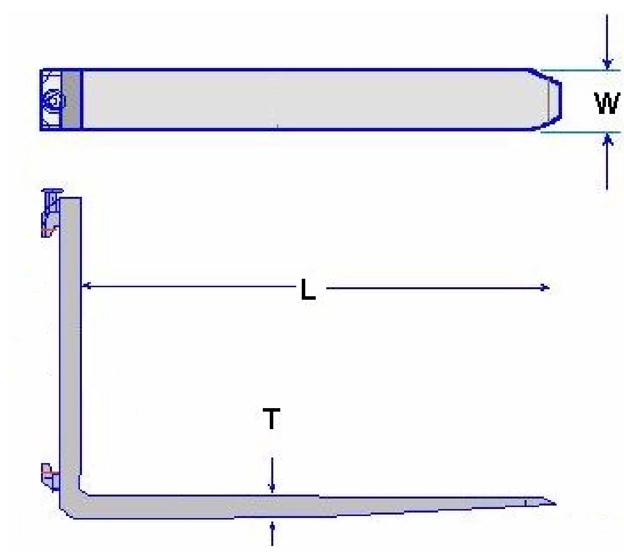


Figure 10: terrestrial forklift tines

Terrestrial forklifts forks (tines) feature a thin profile (dimension T in Figure 10) that tapers to a point. This design is effective because industrial forklifts are usually designed to carry payloads whose center of mass is approximately 24 inches from the root of the tine, with an overall length (dimension L in Figure 10) around 4 feet[4]. Furthermore forklift tines are monolithic solid pieces of metal in order to handle the wear and tear of constant insertion and extraction with minimal structural damage. In comparison, the center of mass of the lunar rovers is situated 5m away from the base of the CLLO (Figure 8). The increased moment due to the greater distance (moment= Force x distance) would require a much stronger structure to support it. Simply thickening and extending the monolithic tine design found in terrestrial forklifts would result in an extremely heavy and inefficient structure. In order to minimize the mass of the structure and the bending forces, the distance between the centroid axis and the edge of the structure must be maximized (following the second moment of area)[2]. As a result, the hollow square beam is the optimal design for CLLO's forks.

In addition to being structurally efficient, the hollow structure of CLLO's forks houses the leadscrew actuator used to extend and retract the outboard fork, as well as the crane assembly used to capture and offload the lunar rovers. Using monolithic forks would require the actuators and cable assembly to be mounted on the outside of the structure, exposing them to the abrasive lunar dust and increasing the risk of damage due to accidental contact or a collision between CLLO and the payload.

4.2.2. TELESCOPING DESIGN

A second characteristic that differentiates CLLO from terrestrial forklifts is the telescoping nature of the forks. Telescoping forks are required for the operation of the offloader, as they facilitate repositioning of the system by pushing the carriage and telescopic tower beyond the edge of the lander (Figure 9). Two configurations of telescoping forks were examined - differing from each other by the position of the telescoping joint- and the following table shows the design trade-off:

Configuration	Characteristics	Advantages	Disadvantages
Monolithic fork	-single fork structure, with translational telescoping joint located at the carriage-fork junction -fork stowed into the PSU unit (see Figure 11 for depiction) -capable of retracting beyond the carriage	-lower mechanical complexity and weight in fork -capable of handling payloads positioned close to the tower structure	-requires major modification of Payload Support Unit (PSU) structure - inability to collapse into itself means the rear end of the fork structure will be projected far past the rear of the carriage structure, posing a safety and collision hazard
Segmented forks	-forks separated into two pieces, one of which collapses into the other in a similar to telescopic crane booms -translational telescoping joint built between the inboard and outboard forks	-no modification of PSU structure required -capable of retracting into itself, reducing the risk of accidental collision with other lunar structures	-requires more material mass (overlap between outboard and inboard forks needed) and greater mechanical complexity -payload positioning proximity lower than the monolithic fork design (minimum distance between the payload and the tower structure is dictated by the length of the inboard forks)

Table 3: Telescoping joint configuration trade table

From the above trade table, it can be concluded that the Segmented forks configuration found in the system's baseline concept is the optimal design, for one chief reason: the monolithic fork requires a substantial modification of the PSU structure beneath the lunar rovers. This violates the requirement of no interference with existing lander structures (see *Stowage* in Table 1: CLLO System Requirements).

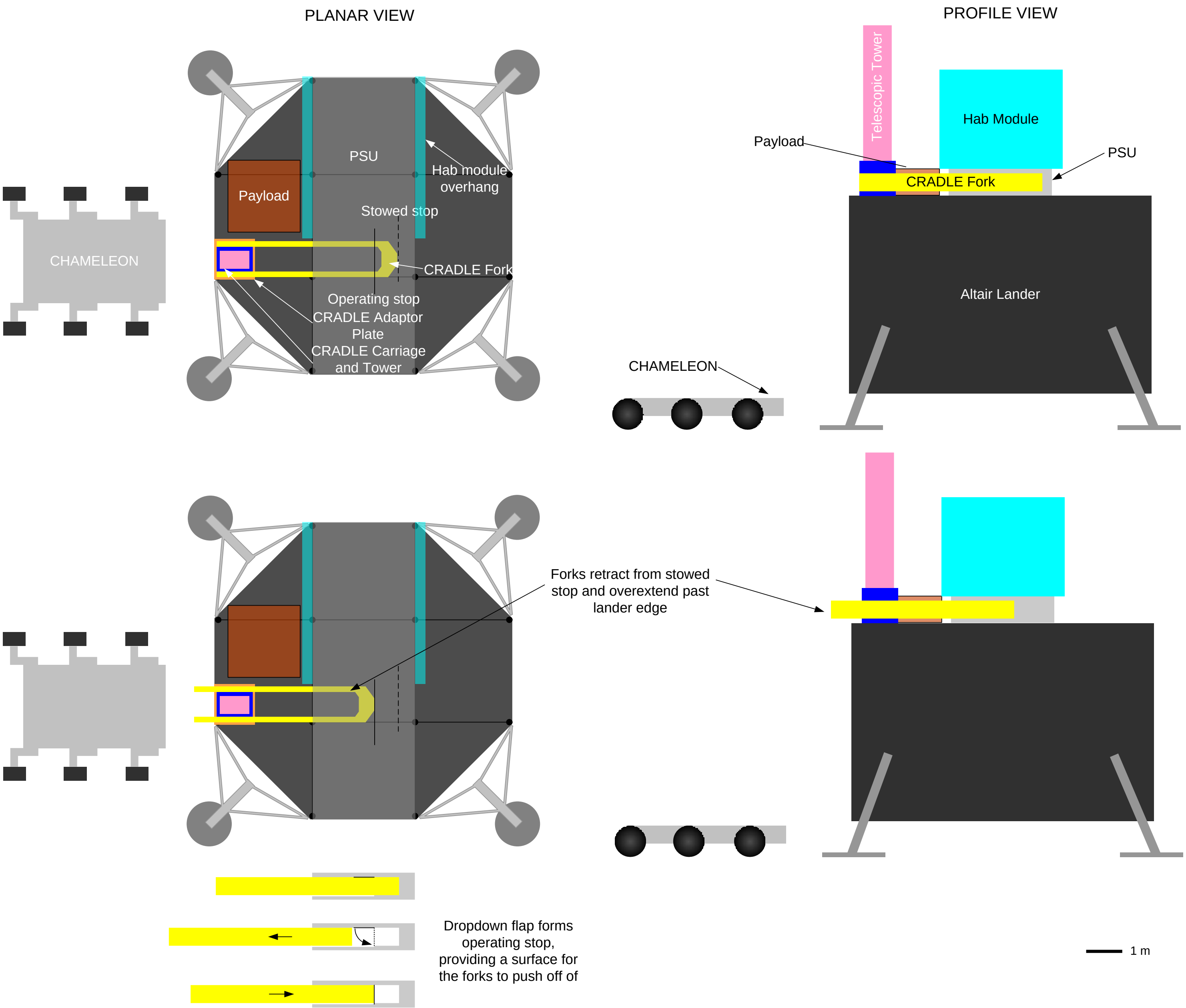


Figure 11: Monolithic fork concept

Figure 12 provides a detailed view of the fork structure and cross section. It should be noted that the outboard forks are larger than the inboard forks, and there exist two structural bridges connecting the two outer forks. The outboard forks are larger than the inboard forks in order to facilitate pallet manipulation, as a smaller outboard fork loaded with a cargo pallet could not be retracted without having the edge of the cargo pallet coming in contact with the inboard fork. The two outboard forks are structurally joined in order to provide a base for the cable assembly and to allow both outboard forks to be controlled using a single leadscrew actuator.

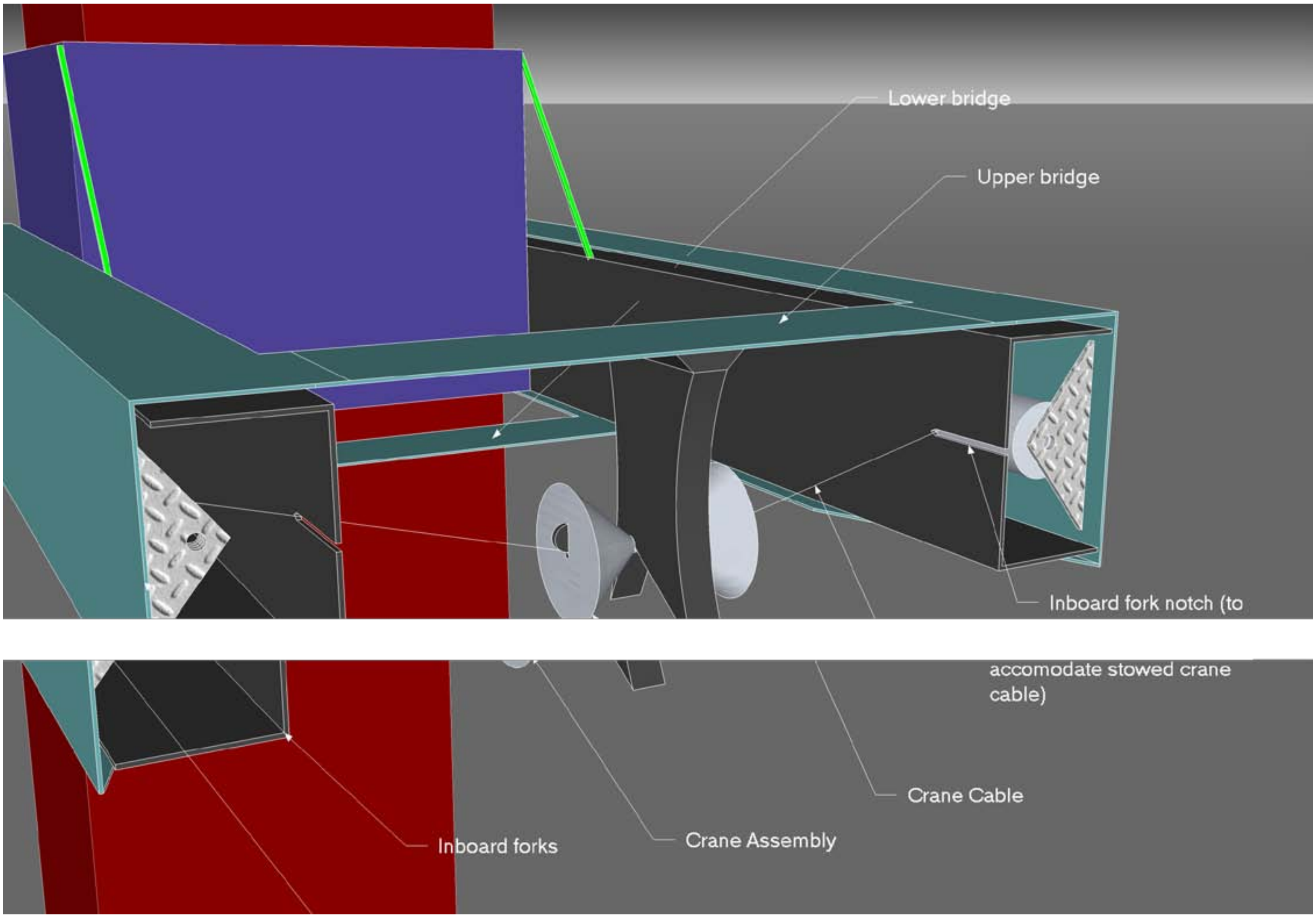


Figure 12: Stowed Fork closeup

4.3. Crane Assembly

As seen in section 3.2.2, the crane assembly exists to facilitate the offloading of the lunar rovers onboard the Altair lander. Two major options exist for the payload interface: active or passive. A preliminary design trade-off can be seen in the following table:

Style of Interface	Advantages	Disadvantages
Active	-greater accuracy -greater chance of docking success in non-optimal conditions (eg. Lander tilt)	-separate power cable required in addition to structural cable -greater mass, power consumption and complexity
Passive	-no power cables needed -lighter, simpler and lower overall power consumption	-harder to dock in non-optimal conditions

Table 4: Payload interface design trade-off

Because of the simpler design and the elimination of a power cable, a passive payload interface system is to be used in the baseline CLLO concept.

4.3.1. Initial Crane assembly Concept

The following images (not to scale) illustrate the design and operational concepts of the payload handling system end effector, found on the end of the crane system's cable. It should be noted that the initial concept featured one cable to which the end effector is attached.

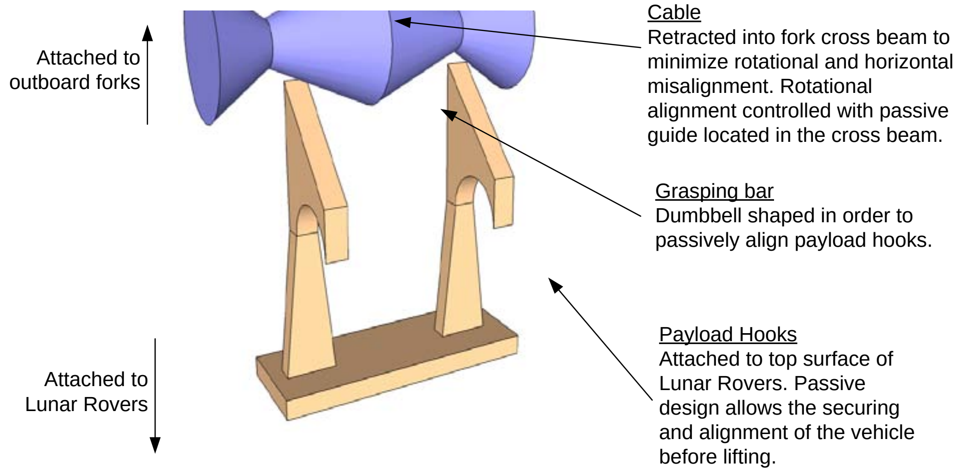


Figure 13: CLLO payload handling system components

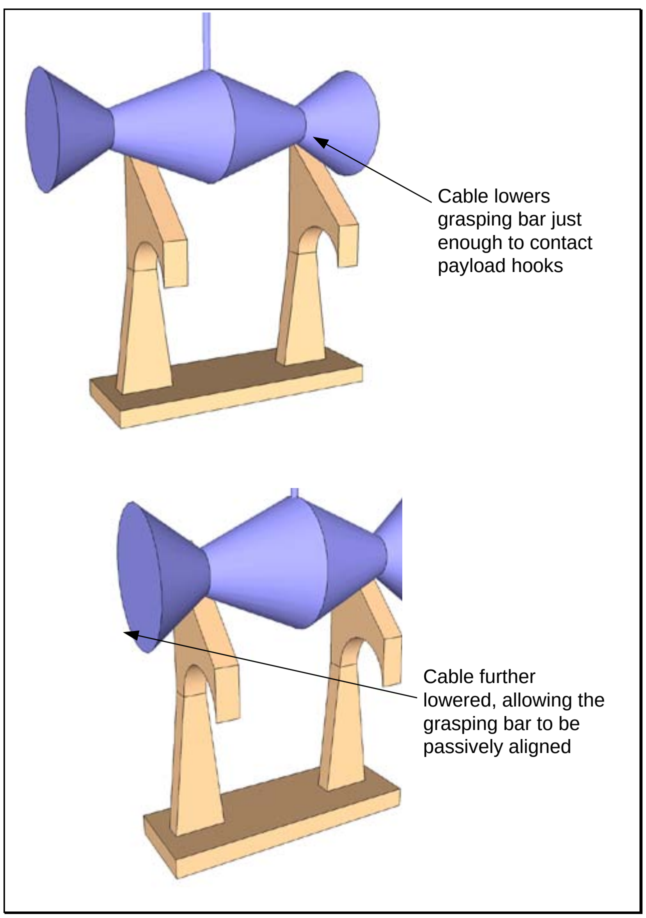


Figure 14: Payload Handling Step 1

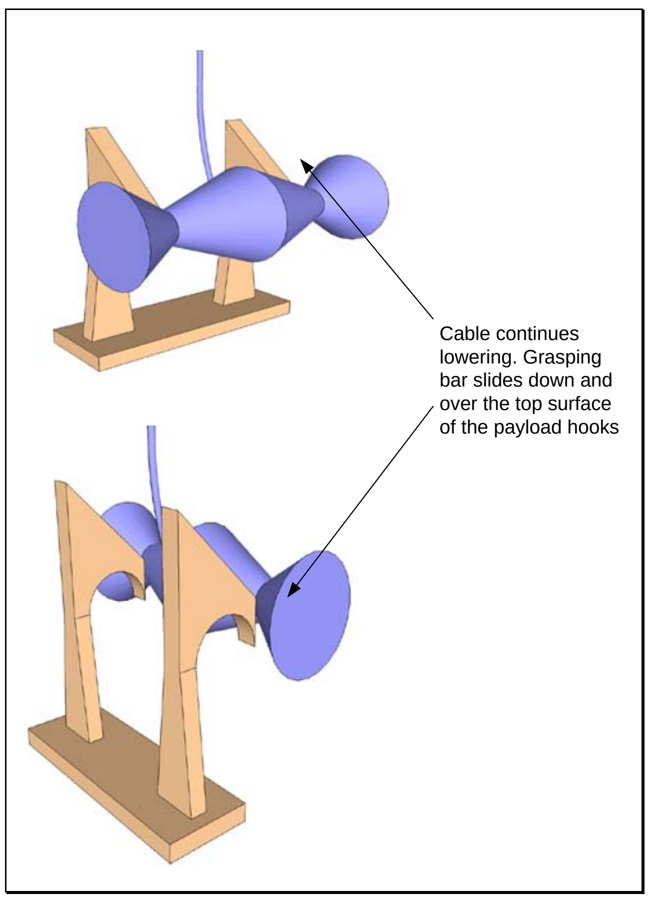


Figure 15: Payload Handling Step 2

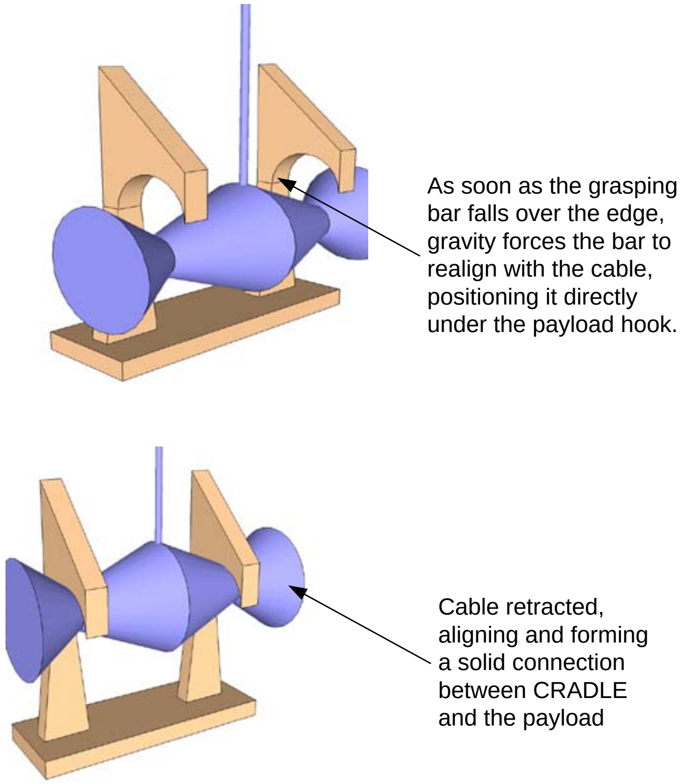


Figure 16: Payload Handling Step 3

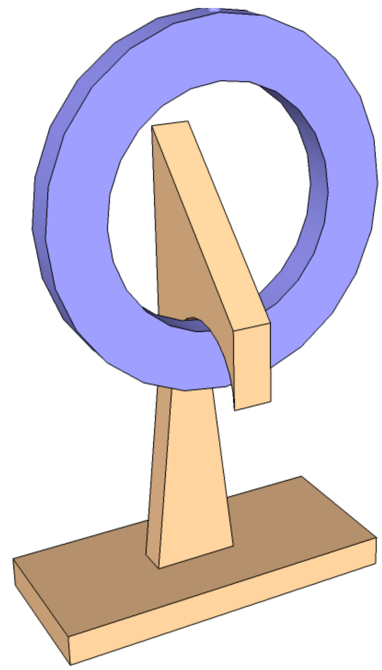


Figure 17: Payload Handling Alternate design

An alternate design for the capture and locking mechanism of the crane system can be found with Figure 17, which performs the same way as the original design, but uses a hoop shaped rather than a dumbbell shape for the end effector. Further testing and analysis is required in order to confirm the optimal size and design of the payload handling interface for the lunar rovers.

4.3.2. Final Iteration

Although effective at dampening horiziontal and vertical mis-alignment, the intial concept was suspended from a single cable point. Systems that use a single cable to lift payloads are inherently susceptible to twisting of the cable as it transitions from a slack to tensioned state. To eliminate this twist, the final iteration of the crane assembly concept features a single continuous cable pulley system. Anchored to the two outboard forks, the cable

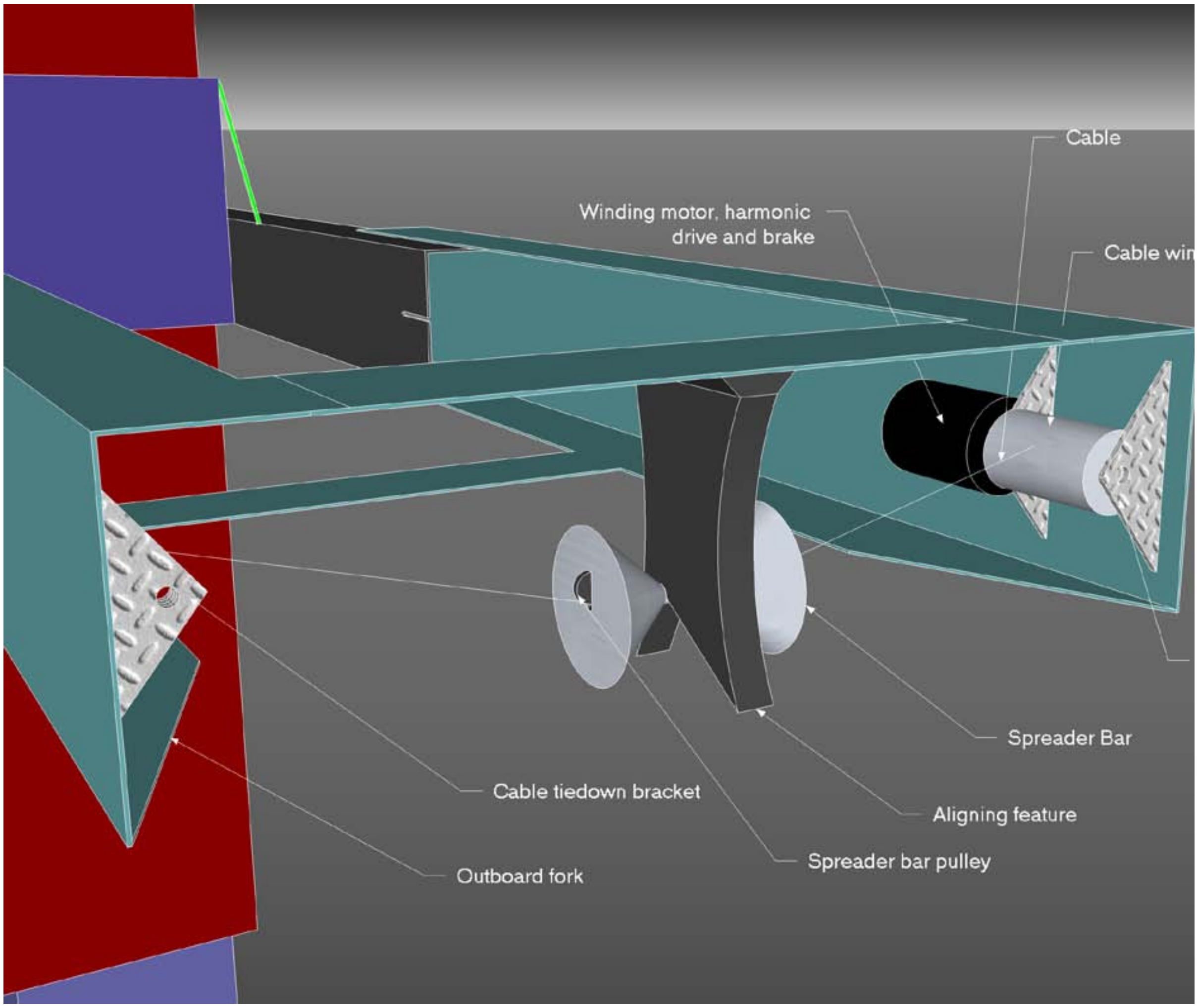


Figure 18: Crane Assembly components

travels through a spreader bar similar in design to the initial grasping bar (Figure 18), suspending the payload handling interface from two points rather than one (Figure 19). This eliminates the possibility of a twisting cable, as the triangular profile of the two cables will resist any rotational movement and return the orientation of the spreader bar to the rest position. This in turn reduces the chance that payloads lifted by the crane assembly will rotate and collide with nearby objects. The triangular profile also serves to dampen pendulum-type oscillations in the lateral direction, while the pulleys found within the spreader bar ensure the payload is always suspended directly beneath the outboard forks.

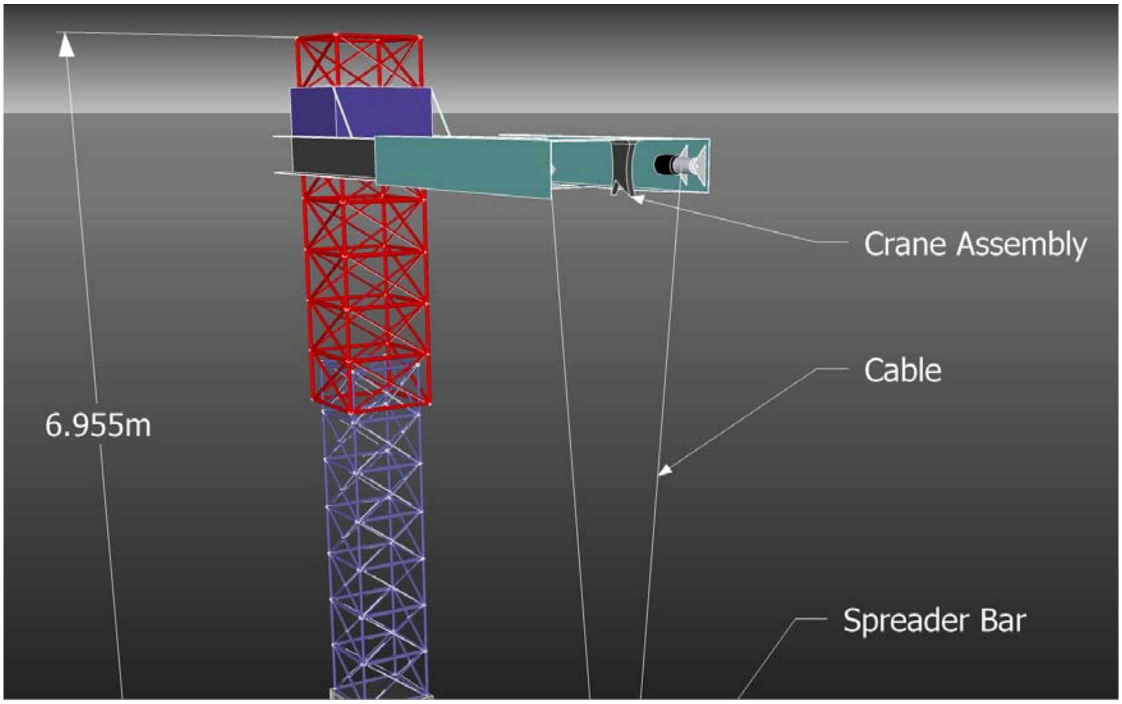


Figure 19: Deployed cable system

4.4. Kinematic Assessment on 12° slope

The CLLO is required to offload payloads when the lander is tilted at a maximum of 12° to the local gravity vector. This tilt is a combination of landing on a slope of 6° and having the legs land on a rock and depression combining to create an additional 6° of tilt. There exist two cases in which a collision between the rover and CLLO could be envisioned.

The first case occurs during liftoff of the rover from the lander deck, where the top surface of the Small Pressurized Module could come in contact with CLLO's forks or the other rover as it realigns itself with the vertical axis. Figure 20 illustrates the restrictions

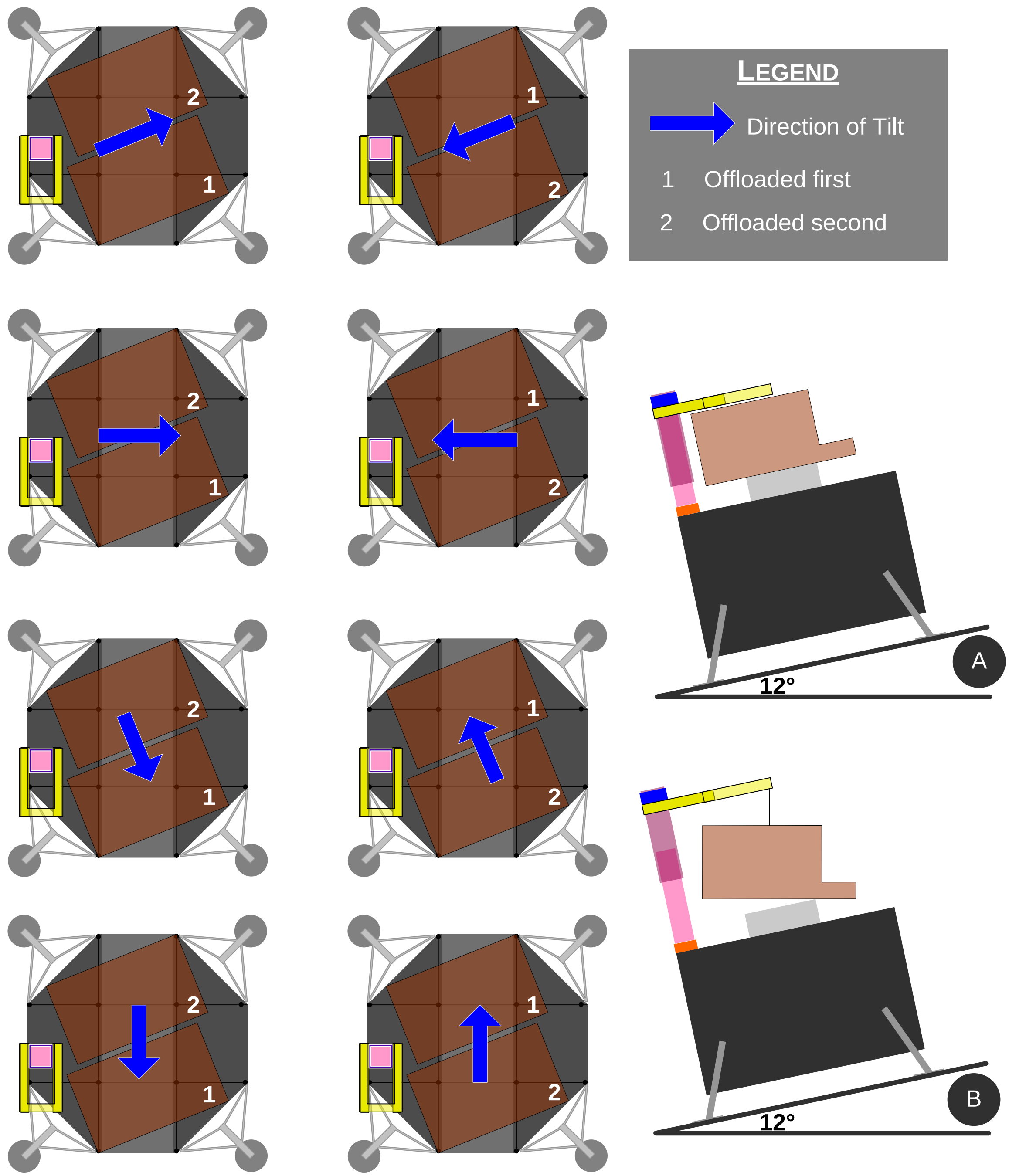


Figure 20: Offloading Lunar Rovers Tilted scenarios

regarding which rover to offload first in order to prevent rover-rover collisions, as well as the procedure needed to be taken in order to avoid a rover-CLLO collision.

As illustrated in the above diagram, offloading the rovers depending on the overall tilt of the Altair lander prevents the rovers from colliding with each other. The lander's tilt ensures that as soon as the rover is lifted off the PSU structure, it will vertically align itself away from the other –still docked- rover. It should be noted that the eight modelled directions in the figure were chosen to correspond with the cardinal directions of both the rover and the lander.

Sub-image A shows the worst case offloading scenario, in which lander and terrain orientation results in the deck being tilted 12 degrees towards CLLO. Retracting the cable to a very small distance such as that shown in Sub-image A and attempting to lift the rover off the PSU structure would result in a collision between the vehicle and the CLLO forks, as the rover swings to align itself with the vertical axis.

In order to prevent this from occurring, both the tower and the forks extend and deploy, while releasing more cable. The result can be seen with sub-image B, where the extra height of CLLO tower and increased cable length allows it align with the vertical axis without coming in contact with the lifting fork. The rover is not expected to swing past the vertical axis similar to a pendulum as the Front end of the rover (closest to CLLO) will lift off the PSU before because of the angle of the lander, and the locking mechanisms between the rover and the lander PSU. Even if the rover was to start swinging, it would come in contact with the side of the PSU before impacting the CLLO tower.

The second case can be found when lowering the rovers to the lunar surface with CLLO located on the highest edge of the lander, as depicted in Figure 21. Fully extended, the reach of the CLLO system provides adequate clearance for the large rover payloads to be lowered to the ground. It should be noted that the rover profile illustrated has been sized to show the worst case scenario of its orientation, with the rover misaligned to the CLLO platform.

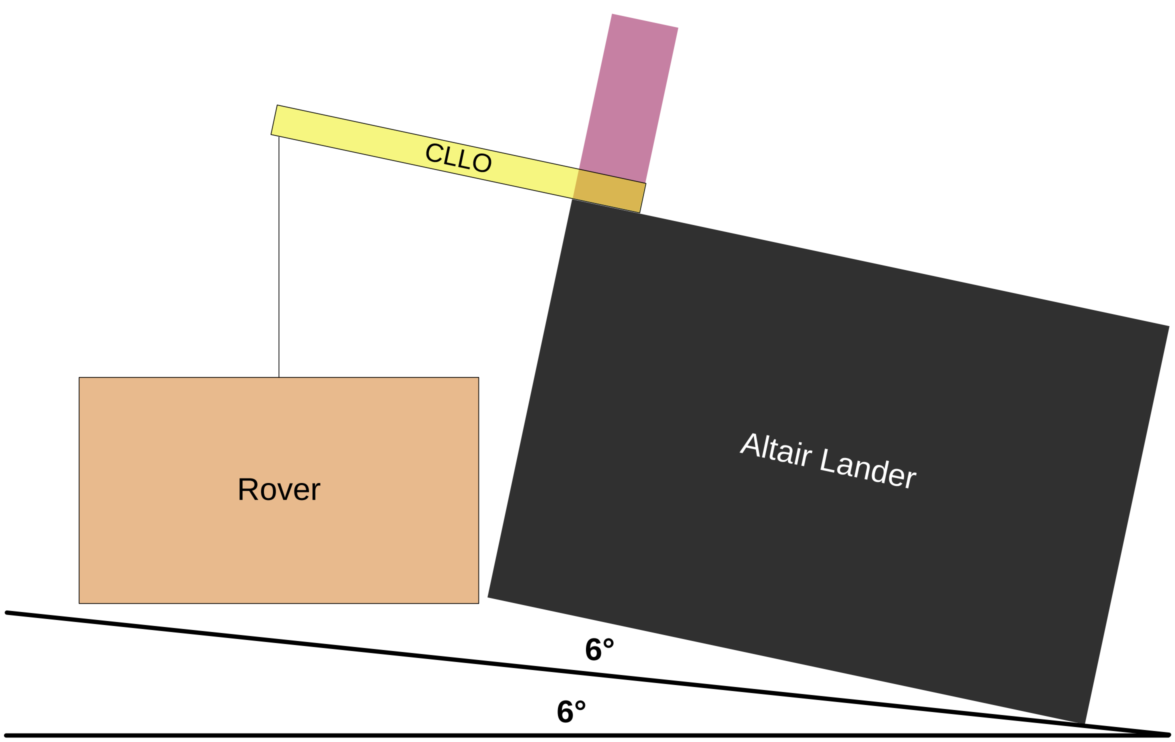


Figure 21: Kinematic diagram of lander mounted CLLO on 12 degree slope

5. Conclusions

There is no one optimal offloader concept.

The expected capabilities and strict size and mass limits imposed on CLLO means the system's final design is not a perfect concept, but actually a compromise. An attempt to redesign the system to optimize one specific requirement (eg. Payload positioning accuracy) would negatively affect another part of the system (mass, power consumption, complexity/mechanical points of failure).

CLLO provides the best mix of accuracy, reliability and versatility of any lunar lander offloading system.

Its five axes of motion, ability to offload both palletized cargo and lunar rovers, and capacity for relocation to another lunar rover for use on the planetary surface make it extremely versatile. The fact that the system can handle the bending moment of a 6000kg lunar rover positioned at the end of a 5m long telescopic fork structure is a testament to its strong structural design. Finally the unique crane assembly limits any lateral and rotational misalignment, allowing for relatively precise manipulation of the lunar rovers without fear of a collision or accident occurring due to twist in the crane cable.

CLLO's design could provide lessons to improve terrestrial forklifts

Telescopic forks and an embedded crane system represent two specific areas where CLLO's design can be used to improve terrestrial forklifts. Telescopic forks could allow for stacked (or two deep) pallet storing, while an embedded crane system could see small sized cranes being replaced with new forklift-crane hybrid vehicles.

6. Recommendations

This section outlines the steps needed to be taken in order to finalize the design of the CLLO and to bring the system closer to implementation and construction.

1. **More detailed design**

   This report only represents a high level conceptual design of a lunar lander offloader concept. A more in-depth analysis and design process would address the more fine details of the concept (eg. positioning of electronic control components, thermal design, actuator placement, radiation protection, etc.)

2. **Prototyping and system testing activities**

   Perliminary structural calculations were performed by other team engineers for the CLLO concept (and as such are not included in this report), however prototyping and testing activities are required in order to confirm the validity and integrity of the structural design. Concepts such as the crane system and palletized cargo offloading sequence may not be found to be unfeasible during testing. Further prototyping activities can also involve testing the use of composite.

3. **Stronger definition of auxiliary payloads**

   Auxiliary payloads was not defined in the system requirements, and was assumed in this report to be considered mountable on a cargo pallet. A more clear definition of what auxiliary payloads are to be handled by CLLO would allow the system to be more efficient and be tailored to those specific payloads.

4. **Examination for auxiliary uses other than offloading**

   Examining additional uses beyond lander offloading would allow the CLLO to play a more crucial role in establishing a more permanent human presence on the moon's surface. Extensions such as a drilling rig, science platform, excavator shovel or fine manipulator (eg. Robonaut attachment point) would allow for the evolution of the CLLO from a mere lunar lander offloader into a multipurpose construction and utility vehicle.

7. References

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