

# CRANE Executive Summary

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	Name
<b>Written by:</b>	Manuel Arias Germán León Pablo Fernández Miaja
<b>Checked by:</b>	Manuel Arias Germán León Pablo Fernández Miaja
<b>Approved by:</b>	Manuel Arias
<b>Authorized by:</b>	Manuel Arias

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# 1. Distribution list

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UVIGO team	Universidad de Vigo		
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# 2. Document Control Data

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Table 3.2-1 TBC Issues

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## 4. Introduction

Lunar Caves, object of exploration for the current mission, are connected to the surface of the Moon through vertical pits of several tens of meters. The floor around those pits, as well as its rim, are partially unknown in terms of material composition, stability, slope, etc. Besides, the size and configuration of the caves are also unknown, in terms of available space for maneuvering through them. Its length, yet unknown, it is estimated in tens of meters. As a consequence, its exploration faces several challenges that can be considered unique in comparison to previous rover-based missions.

Given the uncertainty on the characteristics and dimensions of the caves, the best option for exploring them is using a swarm of small robots (designated as Cave Elements, CE) which will be deployed inside the cave through the vertical pit. Each CE in the swarm will carry out one or several scientific missions, such as 3D-mapping, sample acquisitions, or environmental measurements. Deploying them in the bottom of the pit, given its depth, is challenging and one of the targets of this project. Given the depth of the pit, as well as the length of the caves, solar light does not reach the area in which the robots will operate. The second target of this project is designing a method for supplying energy to those robots. A similar problem affects the data transmission between the surface and the swarm of robots, so a method to overcome this problem is the last sought target.

The proposed solution is using a rover (designated as Surface Element, SE) equipped with a crane, as shown in Fig. 1. This crane can be used to deploy the CEs in the bottom of the pit (i.e. caves) avoiding the unstable terrain around the rim and the protrusions of the pit walls. For doing this, CEs are hold and released by the Head (see section 6.6). The Head is also equipped with a wireless battery charger, connected to the SE Power Subsystem through an electrical wire running in parallel to the mechanical one. Once the CEs are deployed, the crane would keep the Head in the pit, so the CEs can return to it and charge their batteries. The same concept can be applied to the data transmission as it is affected by the same problem: the Head will act as a relay between the CEs and the Rover, which will be the responsible for communicating with the Ground Station given its location in the Moon surface.

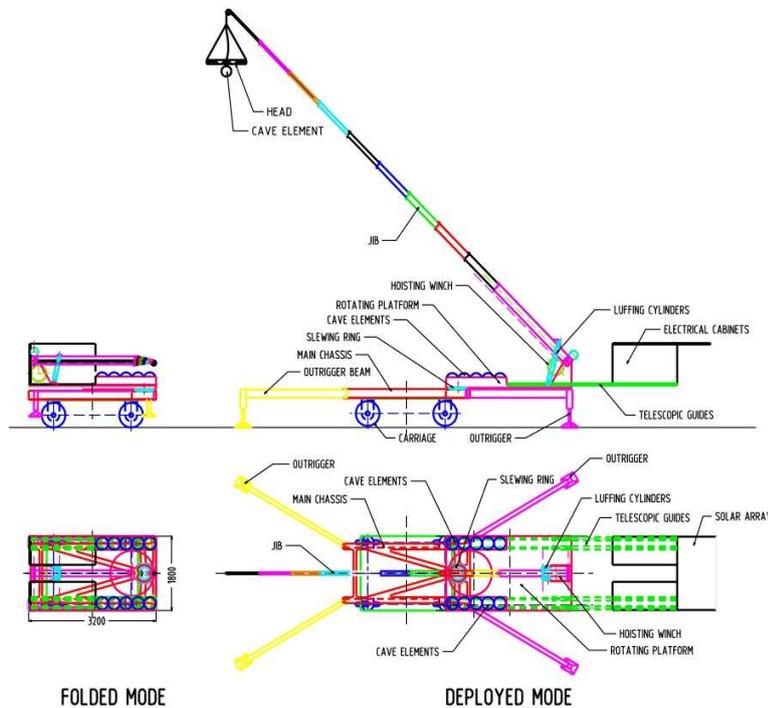


Fig. 1. Surface Element with the telescopic mast mounted (CE not to scale).

Although no specific study on the environmental requirements dictated by the Moon were carried out in the study all the hardware have been based in Space Qualified parts were possible. These parts are capable to work in the thermal environment of the Moon although no specific calculations have been made. Regarding radiation, no specific environmental analysis have been made. However, the mission will last less than one lunar day, therefore problems associated to total ionizing dose are minimized. Again, electronics with space heritage, Cubesat based sometimes, have been baselined where possible. For other custom equipment space grade hardware was selected as a reference. The Moon environment is known to present problems regarding dust. Again, no specific provisions have been made but the mechanical systems were envisioned with simplicity in mind and with the goal that could be easily protected against dust.

## 5. Description of the mission

The landing point of the lander will be set at a safe distance from the pit, considering not only the unstable terrain area around it, but also the uncertainty in the landing maneuver. This represents the lander being several tens of meters (or even a few hundreds) away from the pit. This is a feasible distance for the SE (which is a rover), but maybe not for the CEs, given its size. Therefore, the crane is designed to store the CEs during the taxiing stage, in which the SE approaches to the pit. There is an additional advantage in the SE storing the CEs, which will be described later.

Once the vicinity of the rim is reached, the SE will search for a valid point outside the unstable-terrain area for deploying the crane (preoperational phase). This deployment consists in the SE stabilizing itself using outriggers and extending the mast to overcome the unstable terrain and also the wall of the pit, that may represent a risk if CEs descend close to them. It is important to note that the Crane is not detached from the Rover in any moment. Once extended, the Head, equipped with different sensors (stereoscopic camera, proximity sensors, etc.) will be lowered to determine both, if the descending trajectory is safe and, also, if the floor of the pit is suitable for deploying the CEs and, later, for charging their batteries with the Wireless Charger equipped in the Head. In case of not being suitable, the crane can rotate, without changing the SE position, to search for a suitable descending trajectory and deployment site. Another option is retrieving the mast (and outriggers) and moving the whole SE to another position, repeating the operation for deploying the mast and searching for a valid descending trajectory.

Once a valid descending trajectory and suitable pit floor location are found, the crane will start picking up CEs in the surface and deploying them to the bottom of the pits. There are two options for the picking up. On one, the CEs disembark from the Crane and are picked up from the lunar surface. On the other option, the CEs are picked up from specific point on the crane. This last option implies the mast being folded for reaching the CE in the picking-up location on the crane and unfolding it again for deploying them. Although it is more complex procedure, it is independent from the Moon orography and less prone to uncertainties.

Once all the CEs have been deployed, they can perform their scientific missions. For charging their batteries, given that solar light is not reaching the caves, the crane will keep the Head at the bottom of the pit. That Head is equipped with a wireless battery charger, supplied from the SE power subsystem through an electrical wire running in parallel to the winch cable. The CEs only need to get close to the Head (in the range of centimeters) to charge their batteries. The wireless option easily overcomes the problem of unknown and presumably uneven terrain, which would require a complex system if based on physical contact (i.e. connectors). Moreover, the wireless solution can be adapted to charge several CEs at the same time in case of necessity.

A similar problem will face the data transmission. While in the caves, the CEs will not be able to send or receive data from the Ground Segment, not even from the surface of the Moon directly. The Head will be equipped with all the equipment necessary to become a communication relay, bridging the 50-m of solid rock between the caves and the surface. The data received from the Ground Segment

will be received by the SE, which will then transmit it to the Head. The Head will then transmit the information into the caves, where will be received by the CEs. If necessary, some of them can behave like repeaters, enlarging the distance the data is transmitted into the caves, and overcoming problems related to reflections. CEs can send data using the same path, which can be considered full-duplex. This long-distance communication into the caves is kept for critical-situation information or commands. In any other case, the CEs will send the scientific data they have gathered to the Head (and therefore to the SE and the Ground Segment) during the battery charging time. In that situation, the proximity (and the direct line of sight) makes CE-Head data transmission more efficient. The same is applied to the commands sent to the CE from the Ground Segment.

Once the CEs have finished their scientific missions, they will be recovered by the Crane and conveniently stored in it to minimize the residues left in the cave when the mission is over.

## 6. Mechanical Design

The crane consists in several parts, which can be seen in figure Fig. 1. They are enlisted and described in the following sections.

### 6.1. Rover

The Crane is designed to be considered as a payload that can be attached to the Rover (out of the scope of this project). Nonetheless, given that the mass of any feasible crane design is considerable in comparison to the size and mass of the Rover, the design of the latter cannot be totally independent from the Crane. Also, as has been said, the crane is always attached to the Rover, even during the deployment of the CEs and the operation as relay and battery charge station. This does not restrain the Rover from performing additional scientific missions as long as they are compatible with the Crane operation. An additional condition deals with the necessity of using part of its elements as counterbalance system.

### 6.2. Chassis

The chassis of the Crane (Fig. 2) is the base where the outriggers and the rotating platform are attached to, as well as the system to attach the Crane to the Rover.

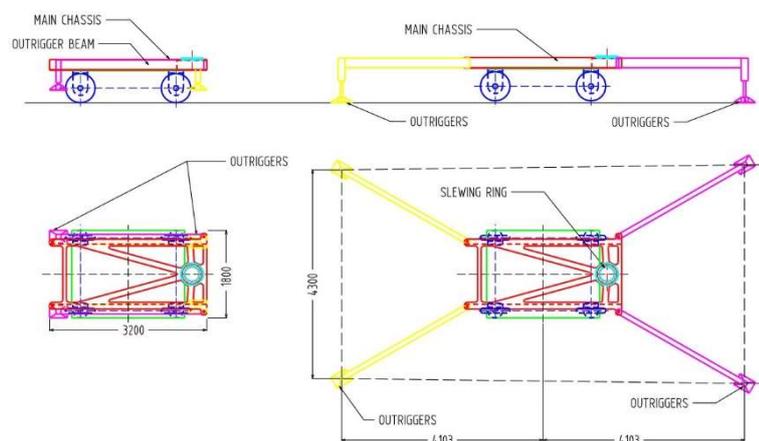


Fig. 2. Chassis of the crane.

### 6.3. Rotating platform

The platform can rotate and changed the mast orientation around a vertical axis. As can be seen in Fig. 2 or in Fig. 1 (slewing ring), this axis is located in the rear part of the Crane (instead on the middle) so the effect of the counterbalance is boosted. This is important given the length the mast must have and the mass of the elements to be lifted. That is why, in Fig. 1, the platform is rotated 180° between folded and deployed modes.

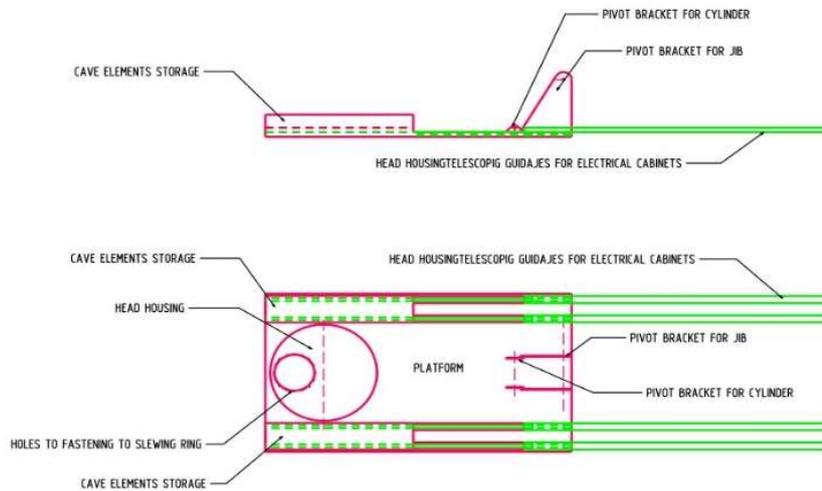


Fig. 3. Rotating platform (deployed and turned to the back of the rover for counterbalancing)

The rotating platform also has a space for storing the CEs before being deployed, so the taxi stage from the lander to the pit does not need to be performed by the CEs on its own. This is relevant because they are presumably not equipped with solar panels and the energy in the batteries may not be enough. Also, the rotating platform has a designated place for the CEs to be lifted from by the crane. In this way, the operation of picking up one CE will be simplified and independent from the orography.

Finally, the rotating platform is also equipped with telescopic guides to move the electric cabinets to the back during the deployment phase and operational phase of the crane. In those electrical cabinets, the solar panels, batteries, and other elements of the rover and the crane are located. The reason is using them as counterbalance so that the crane can be extended to the required length without the risk of tipping over. Although this adds complexity and forces to a joint design of the rover and the crane, it allows not to add additional mass only for counterbalance purposes.

### 6.4. Mast

The mast is folded and stored in a housing until it is extended. Three different types of mast have been assessed: telescopic, scissor-like and caterpillar. The telescopic mast (shown in Fig. 1) is formed by sections in such a way that each one is stored in the previous one (Fig. 4). The first section (closest to the rotating Platform) acts then as the container of the whole mast. Two cables are responsible for extending and folding it. The scissor-like is formed by sections with an x-pattern when extended (Fig. 5). In this case, a linear actuator is used for its deployment. The caterpillar mast is formed by sections rolled around a drum or rolling core (Fig. 6). When this drum spins, depending on its direction, it forces the mast to come out of the container (which has the proper internal shape for achieving this) or it folds the mast back, in a similar fashion to a tape measure.

In Table 1, a summary of their main advantages and disadvantages can be found.

Table 1. Summary of the three masts proposed for the crane

	Advantages	Disadvantages
<b>Telescopic</b>	<ul style="list-style-type: none"> <li>- Very well-known</li> <li>- Compact</li> </ul>	<ul style="list-style-type: none"> <li>- Complex deployment system</li> <li>- Rolling elements are critical given design constraints in space conditions</li> <li>- Difficult to implement a wire for the supplying the repeater in the tip</li> <li>- Changing the length of the mast, during operation, implies releasing and/or retrieving the electrical and mechanical cables (see 6.5)</li> </ul>
<b>Scissor-like</b>	<ul style="list-style-type: none"> <li>- Mechanically simple</li> <li>- Simple Deployment system</li> <li>- Power wire for repeater in the mast tip is easily implemented</li> </ul>	<ul style="list-style-type: none"> <li>- Volume when folded high (around 2.4 m)</li> <li>- Changing the length of the mast, during operation, implies releasing and/or retrieving the electrical and mechanical cables (see 6.5)</li> </ul>
<b>Caterpillar</b>	<ul style="list-style-type: none"> <li>- Simple Deployment system</li> <li>- Power wire for repeater in the mast tip is easily implemented</li> <li>- No deployment wire is needed</li> </ul>	<ul style="list-style-type: none"> <li>- Not tested</li> <li>- Volume when folded high (3.5 m)</li> </ul>

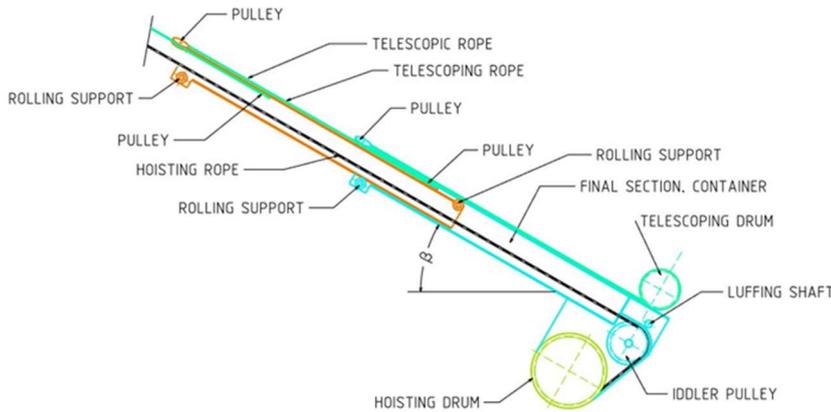


Fig. 4. Detail of the two first sections of the telescopic mast and its deployment system

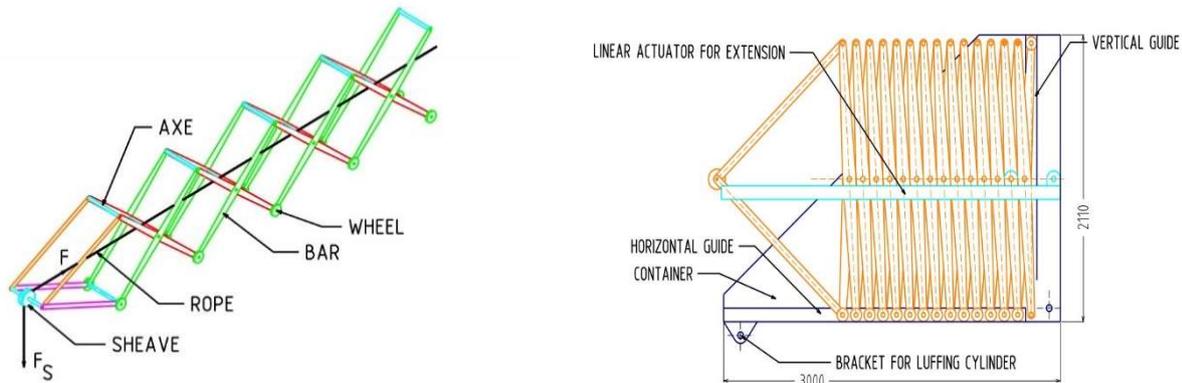


Fig. 5. Scissor-like mast. (left) some section once deployed. (right) The whole mast folded in its container along with the linear actuator and the wheels to ease deployment.

## 6.5. Winch and wires

The winch is responsible for lowering and recovering the Head. It is important to note that two wires (cables) are handled by it. The mechanical wire, responsible of supporting the tensile strength of lifting the Head and the CEs, and the electrical wire, responsible of driving the current from the surface to the pit (from the Crane to the Head). The connection of the electrical wire in the winch must be achieved by slip rings, given its rotating characteristic. On the other hand, its connection to the Head is direct.

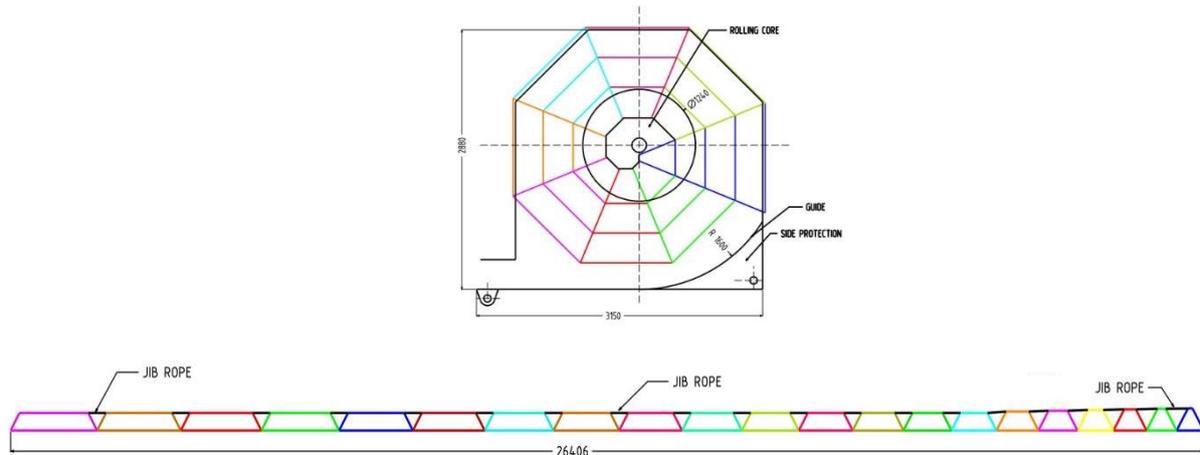


Fig. 6. Caterpillar mast. (up) folded in its container. The rolling core would force the sections to come out through the output in the bottom left side of the container. (down) extended mast

## 6.6. Head

The Head is the core of the system. It is equipped with different elements to explore the pit walls and cave floor to assess the suitability of the descending path and deployment/charging point. It is also equipped with an electromagnet that allows the crane to pick up the CE and deploy them in the bottom of the pit. It includes the wireless battery charger which will allow the CE to charge their batteries. Also, it provides them with a relay to establish communication with the SE and the ground segment.

## 7. WPT Design

The WPT system takes energy from the power subsystem of the SE (supplied from solar panels) and delivers it to the CEs (in the bottom of the pit). As shown in Fig. 7, energy flows through an electrical wire running from the crane to the bottom of the pit, in parallel to the mechanical wire supporting the Head.

The main challenge is reducing the losses associated to that long wire. For doing so, a step-up converter located in the Crane (i.e. in the surface) boosts the voltage to 50 or even 100 V and supplies it to the wire. In this way, for a given amount of delivered power, current driven by the wire is reduced, and so they are the conduction losses as they are current dependent but no voltage dependent. Obviously, increasing the voltage has an impact on isolation, but 50 or even 100 V are standard voltages in space applications and isolation requirements can be satisfied with standard electrical wires. Once in the Head (i.e. in the cave), another converter fed from the electrical wire generates a regulated voltage which is used for feeding all the elements in the Head (communication, sensors, etc.). Both converters are isolated topologies for dealing with the associated problems of long electrical distances and voltage references. This regulated voltage is also supplied to the wireless battery charger. It consists in an inverter which generates a 100 kHz-10 MHz, 0-250 W ac voltage and the transmitting coil. The CEs are equipped with a receiving coil (equal to the transmitting one), a rectifier and a Battery Management System (BMS).

Once the CEs are deployed, the Head will remain hanging over the selected location rather than being placed on the floor, leaving enough space for the CEs to drive below it. Whenever they need it, CEs can come back to the Head and charge their batteries by placing below it (see 1 in Fig. 7). Given that only one wireless charger is included in the Head, a charging-queue protocol has to be established among the CEs so none of them runs out of energy before reaching the charger.

Physical-connection operations are critical, risky, and a source of mission failure, especially considering the unknown orography of the pit floor. On the other hand, wireless charging only requires

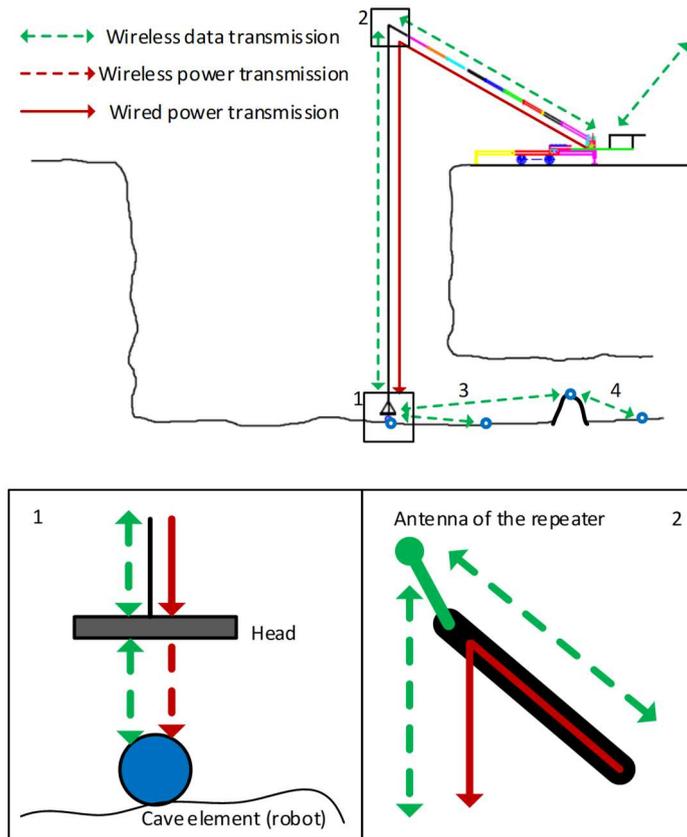


Fig. 7. Representation of power and data transmission between surface and pit. Detail of the mast tip and of the Head-CE interaction. Not to scale.

complying with physical distance and misalignment angle requirements between coils. During the initial exploration of the Head, the floor orography can be assessed to determine if the selected deployment point, which will become the charging point, is compliant or not with those requirements.

Given the criticality of the WPT subsystem, all its elements are redundant, except the transmitting and receiving coils. The reason is that they represent a bulky and heavy component in both, the Head and the CEs. Besides, a failure in any of both, considering that they do not have moving or switching elements, is not likely to occur.

## 8. Comms Design

Given the impossibility of a direct radio link between Earth and CEs, the Earth will establish a radio link with the SE (see green lines in Fig. 7). The SE will establish a link with the Head and, finally, the Head will do the same thing with the CEs. The link between the SE and the Head could rely on a wireless link or a communication cable. Any valid space-qualified wire (e.g. Spacewire or Mil1553) would result in a mass exceeding the capability of the crane, or strongly tailoring the reach of the crane and/or the maximum weight of the CEs. The solution is using a wireless link between the SE and the Head by means of a regenerative repeater at the end (i.e. tip) of the mast (see 2 in Fig. 7), which has a permanent direct line of vision with the Head. In this way, lifted mass for data transmission is cut by one order of magnitude without any relevant drawback. The antennas do not need specific pointing, lacking moving or switching elements.

This communication chain is the only communication path between the surface and the cave, so it is considered a critical part and all the elements are redundant. Besides, given the number of CEs and possible duplicity in the missions, the CE communication hardware is not duplicated.

The Head-CEs protocol will be based on any of the IEEE 802-11 standards, a WLAN, as it can accommodate different data rates, ranges, and link reliability requirements. In general, data exchange will take place while the CEs are charging and, therefore, close to the Head (with a direct line of vision, see 1 in Fig. 7). Nonetheless, it may be necessary to establish communication with a CE (TMTC, i.e. low data rate) while it is performing its scientific tasks inside the cave and far from the Head (see 3 in Fig. 7). Presumably, in that situation there will not be a direct line of vision, and the communication distance will be compromised, even considering reflections. The aforementioned protocol will allow any CE to behave as a relay (i.e. repeater), enlarging the communication distance inside the cave (see 4 in Fig. 7). Moreover, wireless technology has been designed for indoor environments with multipaths. It is important to note that this additional feature does not represent additional mass in the CEs and does not prevent any CE to carry out their scientific tasks, at least, not continuously.

## 9. Parametric Tool

A parametric tool has been designed using a Model Based Systems Engineer approach. It consists in several interconnected Excel spreadsheets, each responsible for the modelling different parts of the proposed system. There is one additional spreadsheet responsible for gathering the main input variables (externally defined) and also responsible for organizing the exchange of data between different system spreadsheets, acting as a kind of concentrator/organizer. This spreadsheet, called Tool Master also gathers the final output variables that define the final design. Each spreadsheet also has a list of input variables which can be considered as inherent to the subsystem; therefore, they are not listed in the concentrator spreadsheet but in the specific one. This still satisfies the rule of “one source of truth”, avoiding the definition of an input variable in several places at the same time, but helps to clearly define the responsibility in the definition of each input variable.

## 10. Proposed solution

Three missions have been studied with the parametric tool:

- Long-mast, light-weight-CEs mission
- Short-mast, heavy-weight-CEs mission
- EL3 mission.

The three of them are presented for the three different types of mast, leading to nine different designs. In this document, only the first one is presented and assessed.

Table 2. Long-mast, light-CEs mission with telescopic mast

Total mass of the mission (Kg)	410	Crane mass (kg)	203.3	Available CE mass (kg)	51.7
Number of CEs	5	Suspended mass (kg)	17.4	Maximum number of CE	14
CE Battery Capacity (Wh)	42	Demanded power-sci (W)	219.6	Maximum CE mass (kg)	3.5
CE charging time (min)	25	Demanded power-ext	940.5		
Cabinet/Fixed mass (kg/kg)	80/75	Charging duty cycle (%)	78.4	Maximum load (kg)	20.9

The parametric tool provides all the parameters of the solution, but in Table 2 the main results are gathered. Considering the electrical features of the CEs, the required charging power is 80.64 W and the demanded power by the crane subsystem to the rover power subsystem while the CEs are inside the cave is 219.6 W. For this calculation, the parametric tool makes a calculation of the efficiency of the converters, the coils for the wireless power transmission and the 50-m cable losses. The wireless battery charger is used during 78.4% of the time. The total mass of the crane is 219.6 kg. Considering that the rover weights 80+75 kg, the available mass for the CEs is 51.7 kg. The maximum weight the crane can lift is 20.9 kg, and the cables and the head weights 17.4 kg. Therefore, the maximum-weight CE that can be lifted is 3.5 kg and maximum number of CEs to be used in the mission is 14. As can be seen the number of CE is 5, considerably lower than 14. The reason is that the limitation comes from the wireless charger duty cycle, and not from the available

CE mass. Another important conclusion is that the weight of the crane is even higher than the weight of the Rover (75+80 kg). Therefore, the crane and the rover should be designed together, rather than designing a crane in such a way that it can be mounted in a predesigned rover.

In Table 3 and Table 4, the same scenario is presented for the other two mast types.

Table 3. Long-mast, light-CEs mission with scissor-like mast

Total mass of the mission (Kg)	410	Crane mass (kg)	171.4	Available CE mass (kg)	83.7
Number of CEs	5	Suspended mass (kg)	17.4	Maximum number of CE	16
CE Battery Capacity (Wh)	42	Demanded power-sci (W)	219.6	Maximum CE mass (kg)	5.1
CE charging time (min)	25	Demanded power-ext	791.1		
Cabinet/Fixed mass (kg/kg)	80/75	Charging duty cycle (%)	78.4	Maximum load (kg)	22.5

Table 4. Long-mast, light-CEs mission with caterpillar mast

Total mass of the mission (Kg)	410	Crane mass (kg)	229.5	Available CE mass (kg)	25.5
Number of CEs	5	Suspended mass (kg)	17.4	Maximum number of CE	12
CE Battery Capacity (Wh)	42	Demanded power-sci (W)	219.8	Maximum CE mass (kg)	2.0
CE charging time (min)	25	Demanded power-ext	928.3		
Cabinet/Fixed mass (kg/kg)	80/75	Charging duty cycle (%)	78.4	Maximum load (kg)	19.4

As can be seen, the scissor-like mast leads to a lower crane weight (171.4 kg) and a higher load capability (22.5 kg). As a consequence, this mast can deploy heavier CEs (5.1 kg) and, at the same time, increase the amount of available weight for them in the lander, leading to more CEs in the mission (16). Nonetheless, the limitation in their number still comes from the wireless charger. Hence, unless its rated power is increased, the advantages provided by the scissor-like mast would be diminished.

The caterpillar mast is heavier than the telescopic (229.5 kg) but with a slightly lower power consumption during deployment (928.3 W). Its main drawback is a reduced load capability for the same reach (17.4 kg). This highly limits the size of the robots that can be deployed (2 kg).

Regarding to communications solutions, semi-autonomous CEs are assumed and the required maximum data rate to explore the cave is 332 Mbps (data link between the CEs, the CH and the SE). This data rate is compatible with the 802.11ac, 802.11ah and 802.11ax protocols. To achieve this radio link, a CE should consume 2.7W, the CH, 1.2W and the end-mast terminal, 0.4 W. Line-of-Sight and the is considered in this analysis, so some CE should act as “mobile repeaters”.

## 11. Conclusions

- The deployment of the CEs inside the cave, the power supply and the data transmission can be achieved with the proposed approach.
- The crane and the rover should be designed as a single unit, not independently, as the proper operation of the crane relies on part of the Rover acting as counterweight and, also, on both (crane and rover) sharing great part of the power subsystem to save mission mass usage.
- The limitation in the number of CEs may come from the available mass for them, once the mass of the crane and the Rover is subtracted from the total mission mass, or may come from the duty cycle (% of usage) of the battery charger. Enlarging the available mission mass (moving to a bigger lander), increasing the charging current of the batteries, multiplexing several experiments in one single CE may be one of the possible relief paths.
- Scissor like mast are significantly lighter than the telescopic or caterpillar ones. However, when stowed, they have be stored in the highest container (around 2.4m for a 20m reach)