# Mast Design Investigation for DomeRanger and PitRanger

## 1 Mission Overview

Payload and Research Investigations on the Surface of the Moon (PRISM) is a NASA program that seeks to explore the lunar surface through the launching of lunar rovers. 2 PRISM missions are relevant in this paper – DomeRanger of the PRISM2 program is a rover whose mission includes investigating the minerology of a silica-rich Gruithuisen dome, and PitRanger of PRISM3 is a rover that will take images of the Lacus Mortis lunar pit, which will be used to construct the internal geometry of the pit. DomeRanger is different from PitRanger in that it will bring already-determined scientific instruments to the dome for data collection, while PitRanger's mission is only about taking pictures of the lunar pit. The missions of both rovers are heavily reliant on their visual perception, which will be contingent upon the correct designs of their masts. The mast of a planetary rover is a stand on the rover that supports the camera at an elevation and possibly allows it to rotate left/right (panning) and up/down (tilting). The mast will play a critical role in navigation for both rovers and collecting high-resolution of the lunar pit for PitRanger.

This paper will take a deep dive into various concepts about the mast and analyze the advantages/setbacks of each of them using the criterions described in the table below.

## 2 Criterions

During launch, the mast may need to be stowed to allow rover-lander integration (e.g. the top of the rover is mounted to the bottom of the lander) and prevent damaged from acceleration. One common stowage strategy is laying the mast against the top of the rover, as what the Curiosity rover did. Upon arrival on the planet's surface, the mast needs to be lifted to an upright posture to operate; this process is known as deployment. The mast needs to have 2 fundamental functions: (1) hold the navigation camera and/or mapping camera, and (2) transition from stowed posture to deployed posture. Its design should also strive for low mass, high accuracy, low structural complexity, and other characteristics as summarized in the table below.

| Factor | Description | Goal |
|---|---|---|
| Mass | Limited to 50kg; leave as much overhead as possible | Minimize |
| Footprint | How much the design affects the space available for other components | Minimize |
| Positional Accuracy | Accuracy of controlling the camera's pose | Maximize |
| Structural Complexity | Simpler design means more robustness | Minimize |
| Vision Ranges | The mast's lift, pan, and tilt abilities and the camera's range of view | Depends |
| Stowage Difficulty | Feasibility and complexity of the stowing mechanism | Minimize |

| | | |
|---|---|---|
| Camera Separation | Whether the mapping and navigation cameras can be the mounted together | Depends |
| Power Usage | Power needed for deployment/lift/pan/tilt | Minimize |

# 3 Design Concepts

This paper explores 2 designs concepts for the mast: the Mast Deployment Drive and the Stewart Platform.

## 3.1 Mast Deployment Drive

### 3.1.1 Background

The Opportunity/Spirit rovers were launched to the surface of mars as part of NASA's Mars Exploration Rover (MER) mission in 2004 to study the traces of past water on mars [1]. The masts of both rovers were deployed in a conical path, swinging from the stowed to the deployed pose in a circular motion about a tilted axis by the Mast Deployment Drive (MDD) [2].

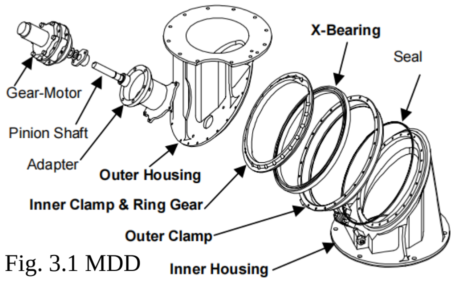


Fig. 3.1 MDD

Fig. 3.1 shows the structural composition of the MDD. The outer ring of the X-Bearing is mounted to the outer clamp, which is mounted to the outer housing (the moving part). The bearing's inner ring is mounted to the inner clamp, which is fixed to the support and features a ring gear. The motor, mounted to the moving part, will rotate the pinion shaft against the ring so deploy the mast. A hard stop at the end of deployment keeps the mast rigid. [2]

In stowed posture, the mast has protrusions that are locked to a mono-pod and a bi-pod on top of the rover (Fig. 3.2). Upon deployment, the mono-pod and bipod electrically unleash their locks and the MDD drives the mast to the deployed posture. [2]

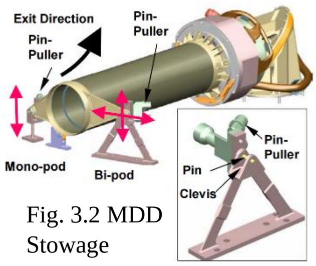
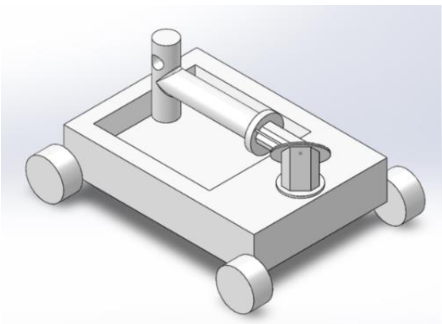


Fig. 3.2 MDD Stowage

Since the motor is mounted on the moving part and rotates against a ring gear in the support, the motor is highly integrated in the mast and takes up less space. And since the mast is locked after deployment [2], its movement is limited as the rover moves and which increases the accuracy of controlling the camera's pose. The MDD also reduces the torque the motor needs to provide, which will be discussed in 3.1.2. Conceptual CADs for this design are presented below to facilitate the following analysis.

Fig. 3.3 Stowed posture



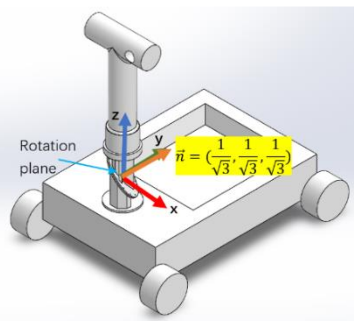



Fig. 3.4 Coordinate system

3.1.2 Torque advantage:

For the sake of comparison, Fig. 3.5 is the ORYX 2.0 rover, which uses a motor to move the mast forward and backward, unlike the MDD which drives the mast in a conical path. We will call this as the “direct lifting” design. When the mast is laying flat on the rover, the torque caused by its gravity is at maximum, which equals $\tau_0 = Lmg$, where $L$ is distance between the center of mass (CM) of the moving part and the axis of rotation, and $m$ is the mass of the moving part. We will come back to $\tau_0$ as a reference.

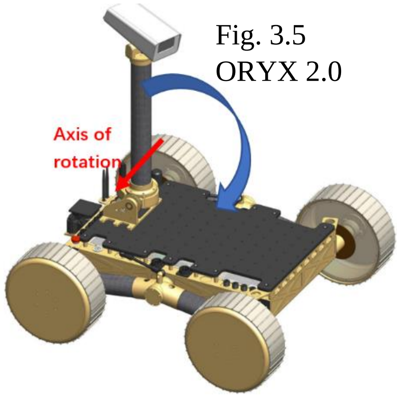
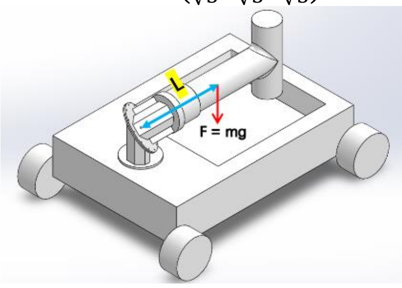



Fig. 3.5
ORYX 2.0

Assuming the bearing is frictionless, we can calculate the amount of torque the motor needs to provide in the tangential direction of the rotation plane to lift the mast. We define the coordinate system as shown in Fig. 3.4, then the rotation plane has a unit normal vector $\vec{n} = \left(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}\right)$. As the mast is deployed, its CM rotates about

Fig. 3.6
Stowed
posture



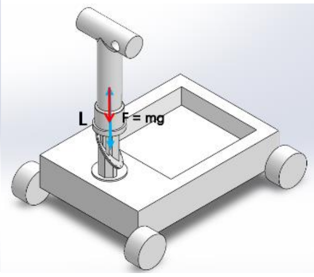




Fig. 3.7
Deployed
posture

the axis given by $\vec{n}$. In stowed posture (Fig. 3.6), the CM is at $(0, L, 0)$, and as the mast swings upward, and the center of mass ends up at $(0, 0, L)$ (Fig. 3.7). To find the torque in the tangential direction, we need the projection of the CM’s position in the rotation plane. The initial position vector projects to

$$\vec{p}^{\,i}_{plane} = \vec{p} - proj_{\vec{n}}\vec{p} = \vec{p} - \frac{\vec{n}\cdot\vec{p}}{\|n\|^2}\vec{n} = \vec{p} - (\vec{n}\cdot\vec{F})\vec{n} = (0, L, 0) - \frac{L}{\sqrt{3}}\begin{pmatrix} 1/\sqrt{3} \\ 1/\sqrt{3} \\ 1/\sqrt{3} \end{pmatrix} = \begin{pmatrix} -L/3 \\ 2L/3 \\ -L/3 \end{pmatrix}$$

The final position vector projects to

$$\vec{p}^{\,f}_{plane} = (0, 0, L) - \frac{L}{\sqrt{3}}\begin{pmatrix} 1/\sqrt{3} \\ 1/\sqrt{3} \\ 1/\sqrt{3} \end{pmatrix} = \begin{pmatrix} -L/3 \\ -L/3 \\ 2L/3 \end{pmatrix}$$

To obtain the position vectors during deployment, we construct an orthonormal basis by taking the cross product between $\vec{p}^{\,i}_{plane}$ and $\vec{n}$. After normalizing, $\vec{p}^{\,i}_{plane}$ becomes $\vec{u} = \left(-\frac{1}{\sqrt{6}}, \frac{2}{\sqrt{6}}, -\frac{1}{\sqrt{6}}\right)$, then

$$\vec{v} = \vec{n} \times \vec{u} = \begin{pmatrix} 1/\sqrt{3} \\ 1/\sqrt{3} \\ 1/\sqrt{3} \end{pmatrix} \times \begin{pmatrix} -1/\sqrt{6} \\ 2/\sqrt{6} \\ -1/\sqrt{6} \end{pmatrix} = \begin{pmatrix} -1/\sqrt{2} \\ 0 \\ 1/\sqrt{2} \end{pmatrix}$$

$\vec{p}^{\,f}_{plane}$, the final position vector, normalizes to $\vec{w} = \left(-\frac{1}{\sqrt{6}}, -\frac{1}{\sqrt{6}}, \frac{2}{\sqrt{6}}\right)$. We then try to find the angle of rotation $\theta$ around the axis of rotation, $\vec{n}$, that transitions the CM from the stowed position to the deployed position:

$$\vec{w} = \vec{u}cos\theta + \vec{v}sin\theta = \left(-\frac{1}{\sqrt{6}}, \frac{2}{\sqrt{6}}, -\frac{1}{\sqrt{6}}\right) cos\ \theta + \left(-\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right) sin\theta$$

It turns out that $\theta = 2\pi\ /\ 3$ (120°) satisfies the equation. Hence, the trajectory of the position vector's projection in the rotation plane is $\vec{w}(\theta) = \vec{u}cos\ \theta + \vec{v}sin\theta$ for $\theta \in \left[0, \frac{2\pi}{3}\right]$.

The gravity vector is constantly $\vec{F} = (0, 0, -mg)$. The projection of gravity in the plane of rotation is given by the difference between itself and its projection on $\vec{n}$, i.e.

$$\vec{F}_{plane} = \vec{F} - proj_{\vec{n}}\vec{F} = \vec{F} - \frac{\vec{n} \cdot \vec{F}}{\|n\|^2}\vec{n} = \vec{F} - (\vec{n} \cdot \vec{F})\vec{n} = \begin{pmatrix} 0 \\ 0 \\ -mg \end{pmatrix} + \frac{mg}{\sqrt{3}}\begin{pmatrix} 1/\sqrt{3} \\ 1/\sqrt{3} \\ 1/\sqrt{3} \end{pmatrix} = \begin{pmatrix} mg/3 \\ mg/3 \\ -2mg/3 \end{pmatrix}$$

Now we have the projection of the position and gravity vectors in the rotation plane, and the tangential force due to the weight of the mast is $\tau(\theta) = \vec{w}(\theta) \times \vec{F}_{plane}$.

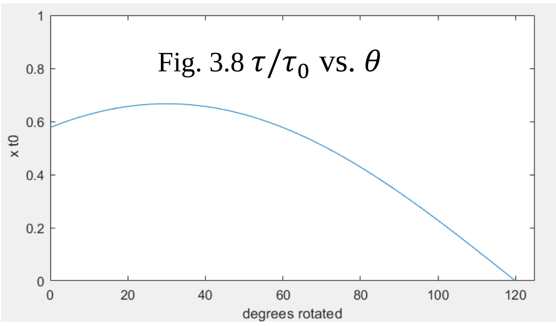


Fig. 3.8 $\tau/\tau_0$ vs. $\theta$

Matlab is used to compute the torque and generate Fig. 3.7, where the horizontal axis shows degrees rotated and the vertical axis shows the proportion of the reference torque $\tau_0 = Lmg$, which is the maximum torque that needs to be overcome for the direct lifting design. The peak torque is $2/3$ of $\tau_0$, meaning a smaller pressure on the motor. Note that we are only looking at the tangential torque with the assumption that the bearing is frictionless. The actual torque is expected to be higher, and the torque in other directions will be withstood by the structural strength of the bearing and needs to be considered when choosing the bearing.

### 3.1.3 Mission Suitability

This design is less effective for PitRanger, who should ideally be able to extend the mast beyond the rover to gain a better view of the pit. Also, because the mast is locked upon deployment [2], the mast cannot rotate forward or backward. But even if the mast can swing back after deployment, the camera would not be facing in the direction of the rover, which may pose a challenge to image processing, so it may be a good choice to just lock the mast in place.

| Factor | Evaluation | Explanation |
|---|---|---|
| Mass | Depends | The MDD may or may not significantly affect mass. |
| Footprint | Lower | The motor is be mounted on the moving part and the overall structure can be more compact. |
| Positional Accuracy | Higher | Hard stop is executed when deployment is finished, after which the mast is locked in place. |
| Structural Complexity | Lower | The MDD's attenuation mechanism involving the ring gear is elegant in that it offers a higher gear ratio while occupying less space. In contrast, |

| | | |
|---|---|---|
| | | having an external motor that lifts the mast with a belt attenuation, as in the direct lifting design, is more complicated. |
| Vision Ranges | Limited | The MDD is essentially lacking the DoF of lifting because the mast is locked after deployment. This may not be a problem for the navigation cameras of both rovers, but the mapping camera of PitRanger may need to be more flexible to see more of the lunar pit's bottom and may need some other mechanism. In contrast, panning and tilting can be achieved by additional motors; for example, the Opportunity/Spirit rovers use an Azimuth Drive for panning. At this stage of development, whether to adopt a panning mechanism has not been decided, but it would be necessary if visual odometry decides on using all 360 degrees of scene around the rover to locate it. |
| Stowage Difficulty | Depends | If without a panning mechanism, the mast would lay on its side (Fig. 2) on the rover, which increases the chances of damage and requires an alternative design to the tri/bi-pod support used by Opportunity/Spirit. |
| Camera Separation | Separated | For PitRanger, the mapping camera may need to be more flexible and may need to be placed at some other place. The downsides of putting the 2 cameras at different positions include a higher mass. |
| Power Usage | Lower | Motor with a lower torque will cost less power. |

3.2 Stewart Platform

3.2.1 Background

Some other mechanisms that have never been adopted but may potentially serve as the mast were also explored. The Stewart Platform is a platform that is connected to 6 motors via 6 lengthenable control arms, which offer the DoFs of elevation, rotation, and tilt. By making each motor push or pull a control arm, the motion of the platform can be accurately manipulated, with a resolution on the order of $10^{-4\circ}$ [3]. The Stewart Platform, however, has never been used as a support for the camera of a planetary rovers, which could be attributed to the following disadvantages.

3.2.3 Mission Suitability

The range of vision is narrow, as the platform can at most tilt a small angle and elevated a little distance. Fig. 3.9-10 show the elevated and contracted poses. The extent to which each motor can extend its control arm should be limited, because as their lengths increase, the platform gets less stable and the control becomes less accurate. Limited length of control arms also limits the platform's maximum rotatable angle, tilt, and reachable height, and the platform may need to work in conjunction with an additional motor that enhances the panning DoF, which would further increase its structural complexity. The platform would not be suitable for PitRanger's mapping camera because it is difficult for the platform to extend the camera away from the rover. A lower elevation limit also reduces the camera's view of the ground near the rover, so it may not be the best choice for the navigation camera. Finally, the platform is unable to stow compactly, as the camera is mounted on the upper part of the platform and cannot be folded against the back of the rover. This therefore would not work for top-bolted stowage, so the lander selection is less flexible.

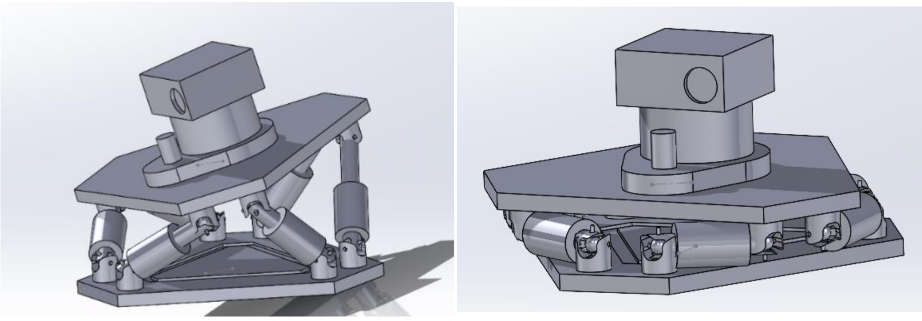


Fig. 3.9-10 Conceptual CAD for Stewart Platform

*serves only for reference

The Stewart Platform is advantageous in its high accuracy, but its setbacks in other areas make it unsuitable as the masts of the PrismRangers. The following chart summarizes the Stewart Platform's features:

| Factor | Evaluation | Explanation |
|---|---|---|
| Mass | Higher | 6 motors and control arms are needed. |
| Footprint | Higher | The Stewart Platform is a bulky assembly and can move around, so one must pay attention to spatial clearance between the platform and other parts to avoid structural interference. |
| Positional Accuracy | Higher | Stewart Platform exhibit high accuracies [4]. |
| Structural Complexity | Higher | Encoders are needed for each motor, and the inverse kinematics of the system is difficult to compute. Wiring is also more error-prone. |
| Vision Ranges | Lower | Due to limited length of control arms, the range of elevation, pan, and tilt are limited. |
| Stowage Difficulty | Higher | The camera mounted on top of the platform is unable to lay down. |
| Camera Separation | Separated | Even if the Stewart Platform is used for the navigation camera, its limited ability to extend the camera beyond the rover makes it unsuitable for the mapping camera. |
| Power Usage | Higher | 6 motors and potentially 1 additional panning motor would require significantly more power. |

## 4. Conclusion

This paper has analyzed 2 mast design concepts: the Mast Deployment Drive and the Stewart Platform. The MDD may hold the navigation cameras for both rovers, because it demonstrates lower structural complexity, higher stability after deployment, and less torque requirement. But for PitRanger, whose mission is to collect high-resolution mapping of the Lacus Mortis Pit, the MDD cannot allow the mapping camera to lean over to see the pit's bottom and is therefore not the best choice. The Stewart Platform, on another hand, would not be suitable for the PrismRangers because its design does not guarantee enough elevation, pan, nor tilt. Even though the range of panning can be expanded by adding another motor, the structure and control of the mast would be too complicated. Its inability to be stowed also restricts the selection of lander, which decreases the chances of proposal acceptance. Hence, the Stewart Platform is overall unsuitable for the missions.

The next steps of the mast development include deciding on whether the MDD remains relevant for the DomeRanger as well as whether a panning mechanism is necessary.

## References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