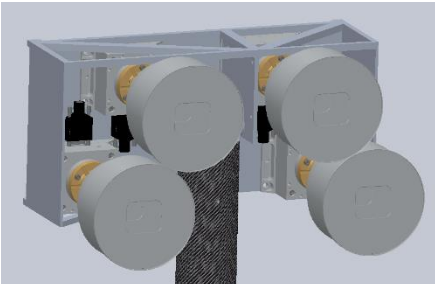
Actuator Selection and Pan/Tilt Concept Development

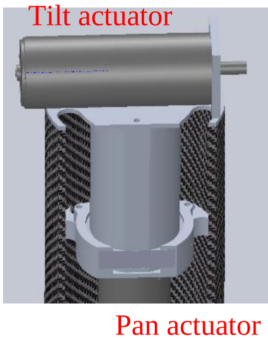
1 Abstract

Payload and Research Investigations on the Surface of the Moon (PRISM) is a NASA program that seeks to explore the lunar surface through launching lunar rovers. In response to NASA's call for PRISM3, CMU is committed to co-developing PitRanger, a rover that will take images of the Lacus Mortis lunar pit to construct the pit's internal geometry. The boom of PitRanger is a stand on the rover that supports the camera and allows it to rotate left/right (panning) and up/down (tilting). The boom will play a critical role in collecting high-resolution pictures of the lunar pit. This report begins with torque analysis, then proceeds to a solution for the pan/tilt actuators, and finally presents a concept of the boom's pan/tilt assembly.

2 Torque Requirement

The pan/tilt assembly provides panning (rotation about vertical axis) and tilting (rotation about horizontal axis) motions for instruments on the masthead. As shown on the right, the masthead consists of the instruments, their enclosure, and mounting. The tilt assembly is everything that is rotated by the pan actuator, including the masthead, tilt actuator, and mounting. The tilt assembly is fixed to the boom through a bearing, while the pan actuator is fixed inside the boom and rotates the tilt assembly through its output shaft.





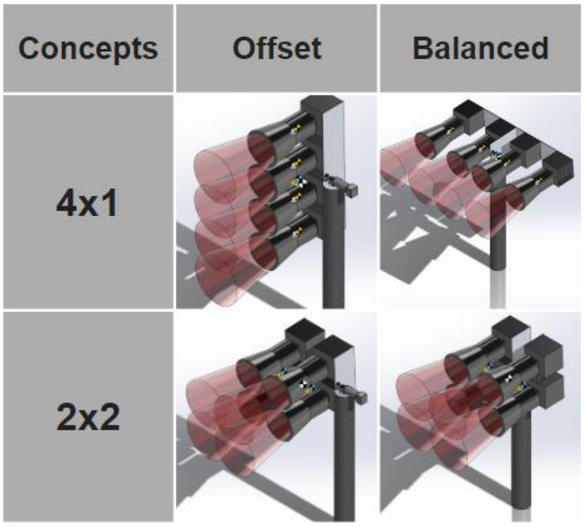
Each actuator needs to overcome the torques that resist its rotation. Such torques come from 3 sources: gravity-induced torque, friction developed within the bearings, and torque due to drag by the wires of instruments.

2.1 Gravity-induced torque

When the boom is perfectly vertical, gravity-induced torque on the pan actuator is 0, but the torque is maximized when the mast is horizontal and is unsupported in the vertical direction. That is, when the mast begins to be deployed and just detaches from the HDRM, gravity of the tilt assembly induces a torque in the direction of panning motion. The figure on the left shows the masthead in this scenario when viewed from the bottom of boom. During deployment, the pan motor needs to hold the tilt assembly at rest by reacting the torque due to its gravity. If its center of mass (COM) is deviated from the pan axis, and the offset is d meter, then the torque is $\tau = mgd$. Torque due to gravity of load would be the most significant torque to be withstood by the pan actuator, so minimizing the offset could drastically

reduce the torque requirement on the actuators.

The current design selects 3 CMOS cameras, 1 bolometer, and 1 DVR, all from Malin, as masthead instruments, which in total weigh 3.52 kg. To be conservative, assume the masthead (instruments, enclosure, and mounting) is 4.5 kg, and the tilt assembly (masthead, tilt actuator, and mounting) 5 kg. There are 4 possible configurations of positioning the 4 cameras, as shown in the figure below.



In 4x1 – Offset configuration, the offset is 68.3 mm from the CAD. In this case, the torque due to gravity would be 0.50 Nm (see table below), but the offset can be reduced to about 0 if the cameras are balanced among the two sides of the boom (the 2 pictures on the right). Because other torques (friction is bearings and wire drag) are negligible compared to the torque due to gravity, it is highly advantageous to minimize this torque. For the purpose of minimizing the load on the pan actuator, it is decided that the balanced configuration should be adapted. Due to manufacturing errors, the masthead's COM of masthead may not be perfectly aligned with the tilt axis, so it is conservatively assumed that the offset is at most 5 mm, in which case the torque due to gravity reduces by more than tenfold, as shown below.

COM offset of tilt assembly (mm)	Maximum torque due to gravity (Nm)
68.3	0.50
<= 5 (balanced cameras)	0.036

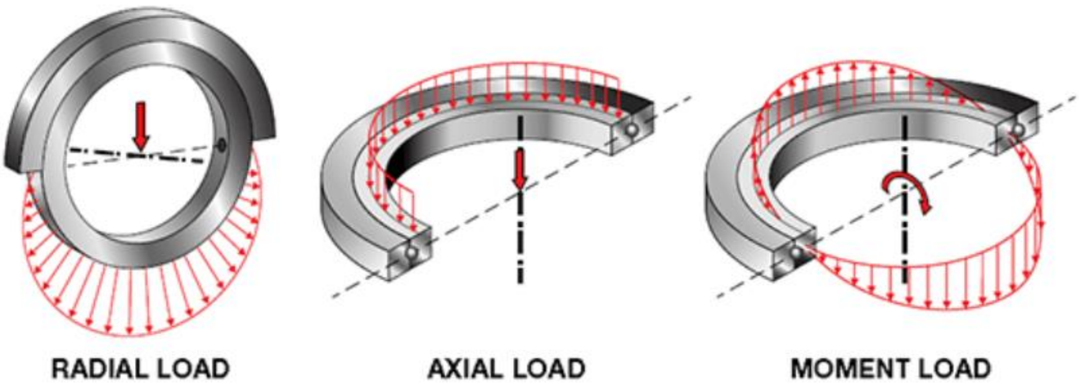
The same strategy is used for minimizing the burden on the tilt axis. The design seeks to align the COM of masthead with the tilt axis as closely as possible. Again, a COM offset of 5 mm is used to estimate the torque. To be conservative, gravity is also assumed to act perpendicularly to the offset vector so that the maximum possible torque is created. The table below shows the torques on the tilt actuator and pan actuator, respectively.

	Mass (kg)	Lunar weight (N)	COM offset (m)	Torque (Nm)
Masthead	4.5	7.29	0.005	0.036
Tilt assembly	5.0	8.10	0.005	0.041

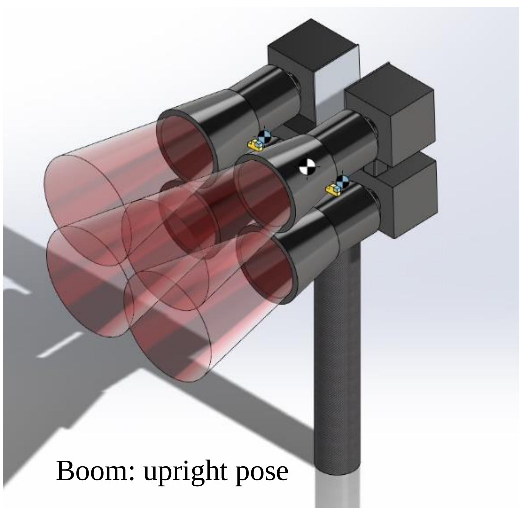
2.2 Torque due to bearing loads

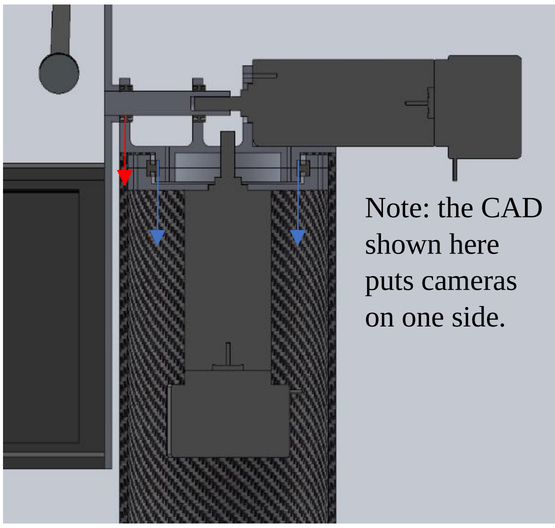
2.2.1 Bearing loads

There are 3 types of bearing loads: axial (thrust) load, radial load, and moment load. As shown in the picture below [1], axial load is the force that acts in the direction of the bearing's central axis, radial load acts perpendicularly against the bearing's inner wall, and moment load is a bending moment on the bearing.



For example, when the boom is upright, there is a downward radial load on the tilt bearing (red) and a downward axial load on the pan bearing (blue). Additionally, if cameras are put on one side of the boom, there will be a moment load acting on the pan bearing. Balancing the cameras among 2 sides effectively removes the moment load and therefore relieves the stress developed in the bearings.





2.2.2 Bearing selection

Kaydon Reali-Slim sealed bearings [2] are used so that lunar dust cannot accumulate in the gaps of bearings. The Reali-Slim series features thin-wall bearings, which are ideal for the goal of keeping the design as compact as possible. The selected bearing types are listed below.

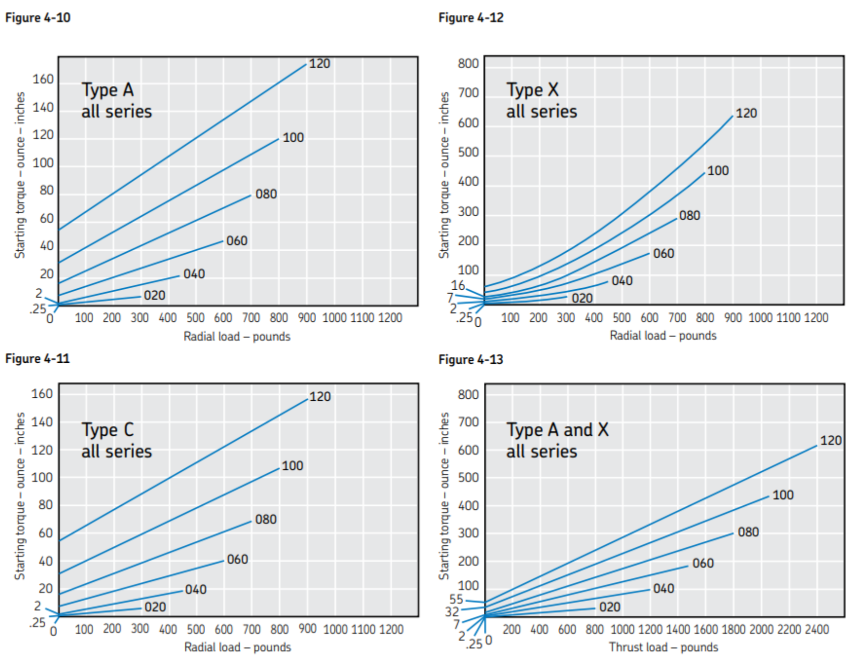
	Tilt	Pan
Bearing	JHA10XL0 [3]	JA020XP0 [4]

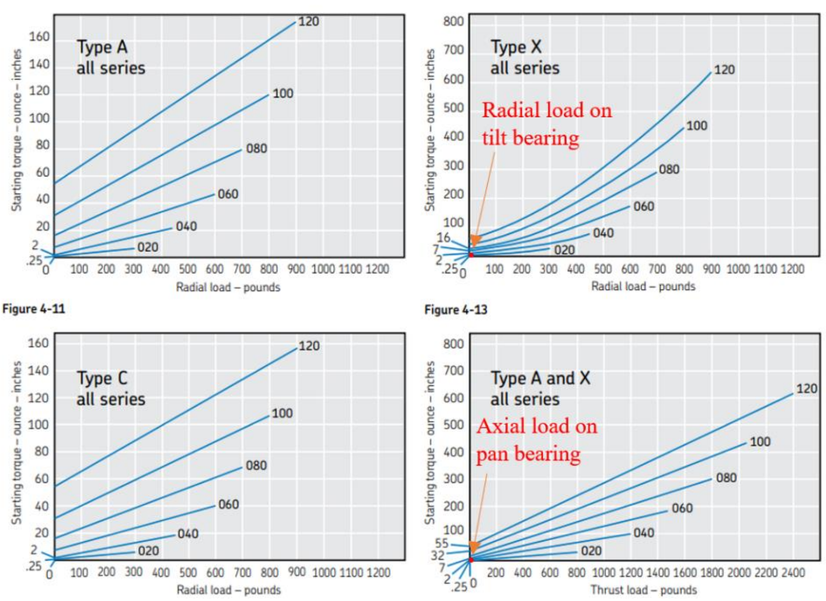
Bearing type	4-point contact	4-point contact
Bore (in)	1.00	2.00
Outer diameter (in)	1.375	2.5

Both the pan and tilt bearings are 4-point contact because 4-point contact bearings are good at withstanding both axial and radial loads. In the case when the boom is not perfectly vertical (e.g. when the rover is on a slope), radial load may develop in the pan bearing, and axial in the tilt bearing. Out of safety concerns, it would be most secure to make both bearings 4-point contact type.

2.2.3 Bearings loads

Shown below are the starting torque vs. load curves of Kaydon bearings [2]. The analysis below assumes the masthead is 4.5 kg, and the tilt assembly 5 kg.





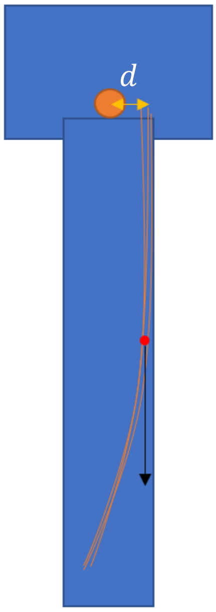
The following table summarizes the torques developed in the tilt and pan bearings, as read off the curves above. Apparently, the resistive torques developed in the bearings are negligible compared to the torque due to the load's gravity.

	Mass (kg)	Lunar gravity (pound)	Torque (ounce-in)	Torque (Nm)
Masthead (radial load on of tilt bearing)	4.5	1.64	0.18	0.0013
Tilt assembly (axial load on pan bearing)	5.0	1.82	0.075	0.00053

Kaydon also provides the maximum bearing loads for the selected bearings [3, 4]. Their maximum loads are summarized in the table below. Since the lunar weight of the masthead and the tilt assembly are below 10 N – much smaller than these values – the bearings are extremely safe for withstanding the load.

Bearing	Axial (lb)	Axial (N)	Radial (lb)	Radial (N)
Tilt JHA10XL0 [3]	370	1646	247	1099
Pan JA020XP0 [4]	790	3514	514	2286

2.3 Torque due to wire drag



The wires connected to instruments in the masthead are estimated to be 175 grams in total. Since it is impractical to estimate the tension developed in the wires under stretch, compression, and twist, the torque due to their gravity is used as a crude estimate of the dragging torque.

As shown on the right, suppose the COM of the wire is d meter away from the tilt axis, then d should be no larger than the inner diameter of the boom, which is 2 inches. That is, the maximum torque is upper-bounded by $mgd = (0.175)(1.62)(0.0508) = 0.014$ Nm. Torque due to wire drag on the pan bearing is expected to be lower than this value, but is conservatively assumed to be equal to this value.

2.4 Total torques

The torques due to gravity, bearing friction, and wire drag are then summed and summarized in the table below:

	Load (kg)	Torque due to gravity (Nm)	Bearing friction (Nm)	Wire drag (Nm)	Total torque (Nm)
Tilting	4.5	0.036	0.0013	0.014	0.051

Panning	5	0.041	0.00053	0.014	0.056

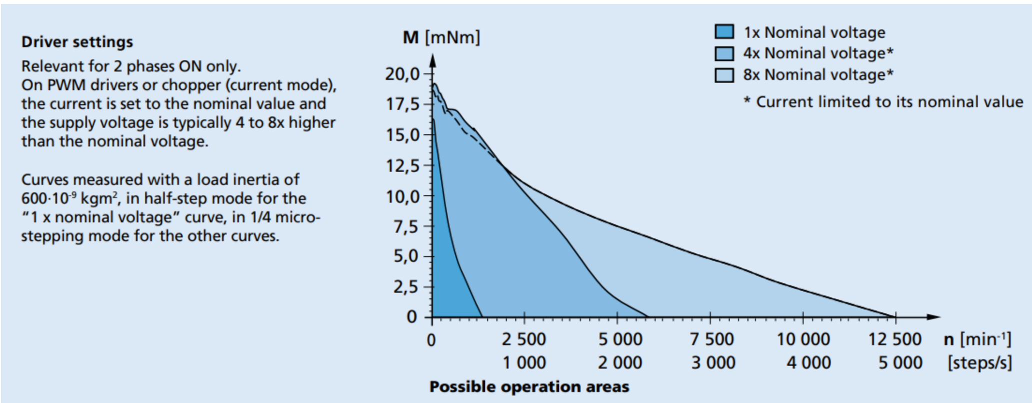
3 Actuator selection

2 types of motors are considered: BLDCs and stepper motors. BLDCs can create high output torque at various speeds, require less power, but are harder to control. Stepper motors, on the other hand, are designed to hold load in place with high, repeatable positional accuracy and are suitable for low-speed applications. They are much easier to control compared to BLDCs, but consume significantly more power. Because the mission is to acquire accurate mappings of the Lacus Mortis lunar pit, positional accuracy is a top priority, and stepper motors can control the increment of pan/tilt angles to a very high resolution. Besides, the majority of power consumption due to is computation, and the power of actuating the stepper motors would not be a blocker. The masthead also does not need to be panning or tilting at high speeds, since the transition between 2 mapping poses are short, so stepper motors are a good fit.

3.1 Actuators

Based on the torque specification discussed above, a combination of actuators is given as follows. Note that the same selection applies to both actuators. Using the same type of actuator is convenient because the motor control can be reused.

Motor	Gearhead	Encoder
Faulhaber AM2224 [5]	Faulhaber 22GPT [6]	Faulhaber PE22-120 [7]
Holding torque: 22 mNm 15 degrees/step Mass: 32 g Angular accuracy: ± 10% 	Reduction ratio: 196 Backlash: 0.8 degree Efficiency: 78% Mass: 82 g 	120 lines/revolution Incremental *Shown with motor mounted 



Shown above are the torque-speed curves of AM2224 [8]. Assuming the masthead pans and tilts at maximum 15 degrees per second (1/24 revolution per second; 2.5 rpm), the motors would need to rotate at $(1/24\ rpm)\ (24\ steps\ /\ rev)\ (196) = 196\ steps\ /\ sec$. At nominal current and 1x nominal voltage (the curve at the bottom), the motor can output up to a 6.5 mNm torque. After 22GPT reduction, the output torque is $(0.0065)(196)(78\%) = 0.994\ Nm$.

	Required torque	Output torque (Nm)	Factor of Safety
Panning	0.051	0.994	19.5
Tilting	0.056	0.994	17.8

These FOS values guarantee that the output torque is adequate and actuation can be done. The output torque, if necessary, can be increased by raising the voltage above the nominal voltage. With 8x nominal voltage and micro-stepping, the output torque can increase over twofold [8]. AM2224 has a nominal power of 1.5 W, as determined from its nominal voltage and current [8], and if it turns out necessary to apply 8x nominal voltage, then the motor's power consumption would be no more than 12 W.

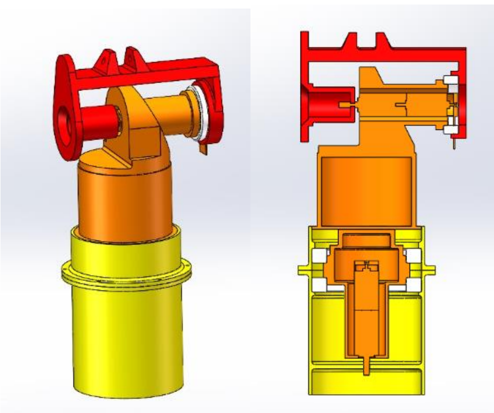
3.2 Control resolution

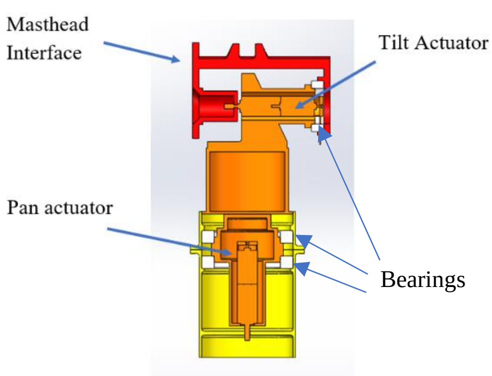
AM2224 rotates 15 degrees per step with angular accuracy of 10%, which means that in every step, it rotates by 15 ± 1.5°. Since an incremental encoder is used, the motor's position can be determined to be within 1.5°. This means that the pan/tilt angles can be controlled by increments of $1.5°/196 = 0.077°$, and their angular error are upper-bounded by $1.5°/196 = 0.0077°$. The most significant limiter on the pan/tilt angular accuracy is the gear backlash. 22GPT is a 3-stage planetary gearhead with 0.8 degree backlash, which is the typical minimum backlash achievable by this type of gearing. Together, the angular error of pan and tilt is at most $0.8 + 0.0077 = 0.808$ degree. An angular error below 1 degree may be sufficient for the mapping.

4 Pan/Tilt concept

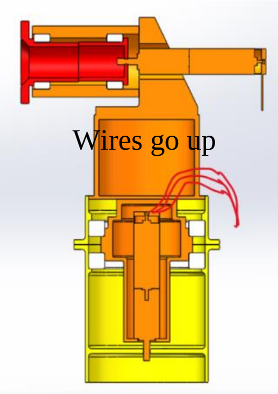
Below is a crude design, with a revision, that only illustrates a concept for the pan/tilt assembly and does not reflect the actuators chosen above. The design and its revision, after discussion, were rejected in favor of a simpler, more reasonable design. The latter has been presented in earlier parts of this report and is closer to the final design.

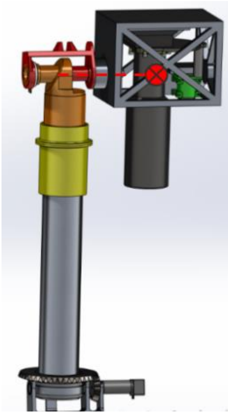
In the pictures below, each color represents parts that are relatively stationary with each other. A downward-pointing motor whose output shaft is fixed to a plate mounted





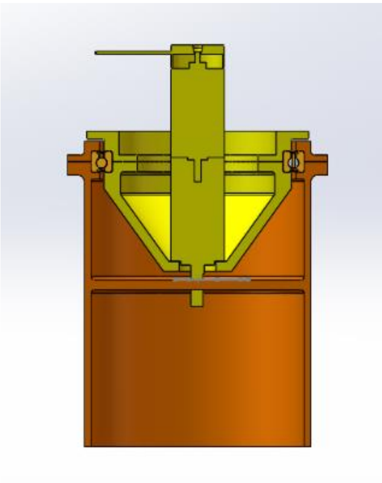
within the boom rotates with the tilt assembly and thereby provides panning. This is done in the hope to put the motor closer to the exterior to help with cooling (which will be discussed later). The orange part is the tilt assembly and is constrained in the vertical direction through 2 bearings mounted within the boom. The horizontal tilting motor provides tilting motion for the masthead through the horizontal bar shown in red. The bar is constrained in horizontal direction through a bearing on the opposite end of the motor's output. The masthead is connected to the same side of the output of the motor, with its COM aligned with the motor's axis.





One consideration of making the pan motor point downward is so that its wire can be led out from above and would not be twisted or stretched by the motion of panning. Also, the wiring of the tilt actuator can be potentially bundled with the wire of the tilt motor before going into the rover body, which represents a more elegant solution for wiring. Note that the design shown above does not reflect this wiring scheme, which would only be applicable if the top of the boom is sufficiently close to the pan motor. Another purpose of pointing the motor downward is to make the it closer to the top of mast to facilitate cooling, which nonetheless turns out to be a naïve consideration because cooling cannot be enhanced unless the motor is directly exposed to vacuum. This concept also comes with a list of downsides, including higher mass, greater structural complexity, and increased footprint on the tilt assembly. Unless there exists an advantage that is significant enough to offset all these disadvantages, this design should not be used.

Shown on the right is a design revision that seeks to expose the motor while reducing mass and structural complexity. To make the design more compact, 2 bearings used to secure the tilt assembly to the boom are reduced to 1, and the pan motor is positioned on the top of the boom to facilitate wiring and enhance cooling through direct contact with vacuum. Exposing the motor, however, poses serious difficulty on the spatial layout of the tilt actuator and its mounting. A strong signal for rejecting the revised design is that it does not even necessarily improve cooling. While exposing the motor to vacuum opens a way to radiate heat, the radiation from the sun could make the motor hotter. Locking the motor inside blocks sun radiation, and methods such as Peltier cooling can be adapted to radiate the heat produced by the motor itself. After examining the above caveats, the faults of the design were deemed to be irremediable and therefore led to the discontinuation of development.



5 Conclusion

This report starts with torque analysis and uses the results to decide on a selection of the pan/tilt actuators. FOS and positional accuracy achievable by the actuators are also discussed. After that, it describes an early-stage conceptual design of the pan/tilt assembly, explains its downsides, and concludes that it not be used. However, it can provide insights into the various considerations when designing the pan/tilt assembly.

6 References

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