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Design and Manufacturing of Extremely Low Mass Flight Systems

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Abstract

Extremely small flight systems pose some unusual design and manufacturing challenges. The small size of the components that make up the system generally must be built with extremely tight tolerances to maintain the functionality of the assembled item. Additionally, the total mass of the system is extremely sensitive to what would be considered small perturbations in a larger flight system. The MUSES C mission, designed, built, and operated by Japan, has a small rover provided by NASA that falls into this small flight system category. This NASA-provided rover is used as a case study of an extremely small flight system design. The issues that were encountered with the rover portion of the MUSES C program are discussed and conclusions about the recommended mass margins at different stages of a small flight system project are presented.

Introduction

The MUSES C Nanorover Mission

The MUSES C mission is conducted by the Japan Institute of Space and Astronautical Science (ISAS). The MUSES C spacecraft will navigate to a rendezvous with an asteroid and then drop markers onto the asteroid surface for targeting. The spacecraft will then descend to the asteroid surface for a momentary touchdown, at which time a projectile will be fired into the asteroid surface. The debris generated from the projectile will be captured in a cone-shaped collector and guided to a sample container. The spacecraft will fire its engines to rise approximately 20 kilometers from the surface and maintain that position while obtaining remote science data on the asteroid.

NASA is contributing to the MUSES C mission in several ways. One of the many aspects of the NASA contribution consists of a small rover, called the Nanorover, which will be dropped off from the MUSES C spacecraft while the spacecraft is still at an altitude of 20 to 30 meters above the asteroid and descending. The Nanorover will then free-fall and impact the surface of the asteroid, landing at a large enough distance from the spacecraft to prevent the plume produced by the spacecraft engines on ascent from blowing the Nanorover off the asteroid surface. Once the MUSES C spacecraft has obtained a sample of the asteroid and risen to its parking orbit, the Nanorover will begin its mission. The first part of this mission involves a fully autonomous self-righting of the Nanorover vehicle combined with determining its location using a star map.

The Nanorover was built by NASA's Jet Propulsion Laboratory in Pasadena, California[1]. The Nanorover is significantly smaller than the Sojourner rover that was deployed on the surface of Mars in 1997. A side-by-side comparison of the Nanorover and the Sojourner rover sitting on one of the side petals of the Mars Pathfinder lander is shown in Figure 1. The mass and volume of the Nanorover are both approximately one-tenth of the Sojourner rover's mass and volume. The Nanorover is made to operate in a 20 micro-g environment, which requires additional mobility functions that the Sojourner rover did not have. Additionally, the Nanorover carries one more instrument than the Sojourner rover, has greater computing capabilities, and has a higher performance camera and hazard avoidance system. The need to fit this increased functionality into the small volume of the Nanorover meant that the component parts would all be very small.

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[1] The Nanorover portion of the MUSES C mission was cancelled and will not fly with the MUSES C spacecraft. The Nanorover was completed through component fabrication, assembly, and some testing.

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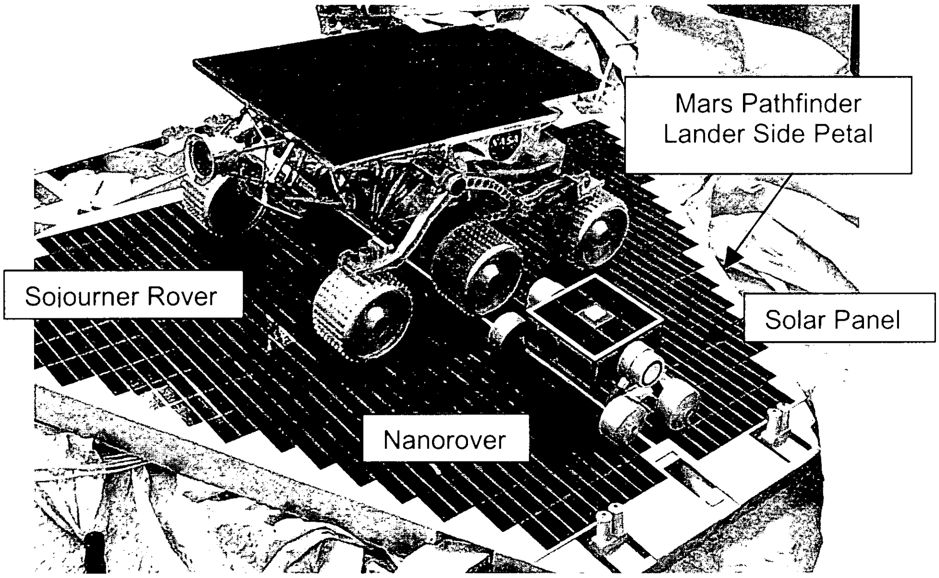


Figure 1. Comparison of Nanorover to the Mars Pathfinder Sojourner Rover on a Mars Pathfinder Lander Side Petal (Demonstration Models)

Nanorover Configuration

The Nanorover configuration with four wheels and the internal components is shown in Figure 2. The body dimensions are 140 X 140 X 85 millimeters. Power for the Nanorover is obtained from solar cells with a switching power supply to generate the required regulation and additional voltages for the complete system. The electronics subsystem consists of a computer; analog interface circuitry for the instruments, mobility, and engineering measurements; brushless dc motor driver electronics for operation of the ten motor driven functions on the Nanorover; and a radio for command and data communications directly to the MUSES C spacecraft.

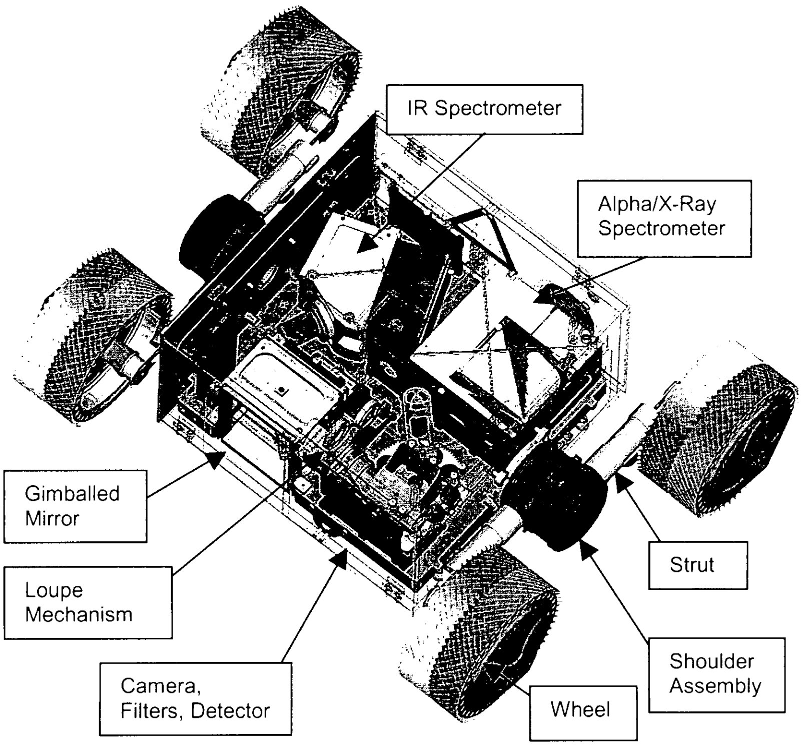
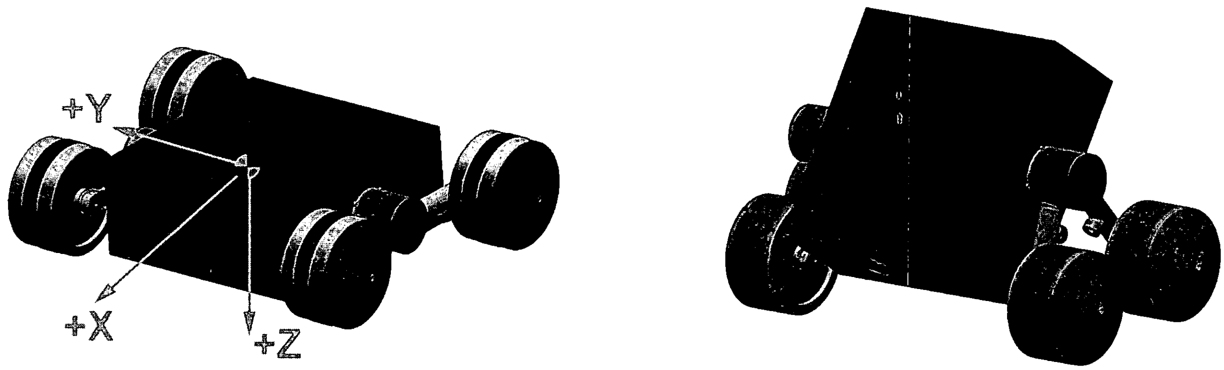


Figure 2. Nanorover Configuration

The Nanorover instruments are composed of an imaging camera with three focal lengths and nine filters with a clear position, an Infrared spectrometer for determining the molecular composition of the asteroid, and an Alpha/X-ray spectrometer for determining the elemental composition of the surface. Additional items in the Nanorover are sun sensors, a laser range detector for measuring distances, a source for in-situ calibration of the IR spectrometer, surface contact sensing in the wheel rims, and unidirectional treads on the wheel surface.

Some of the mobility capabilities of the Nanorover consist of the ability to turn itself over if it ever ends up on its back, turn in place steering, driving velocity control from 0.04 to 200 mm/sec, raising, lowering, and positioning of the body relative to the surface by closing and opening the struts that support the wheels (see Figure 3), attitude determination using star scanning techniques, and microgravity "hopping" to travel large distances quickly. The hopping maneuver is accomplished by the rapid driving of the struts together (going from Figure 3A to Figure 3B) to achieve a vertical velocity of the Nanorover's center of mass. The wheels are driven forward at the same time as the struts are driven together, producing a controlled horizontal velocity. The relative magnitude of the two velocities determines how far the rover will travel during the hop.



(A) (B)

Figure 3. Two views showing the Mobility System's Flexibility to Position the Nanorover Body in Different Poses

Constraints on the Nanorover Design

Several resource constraints were imposed by the spacecraft system on the Nanorover, the usual ones being power, mass, and volume. Additional constraints were derived from the radio communication requirements to the spacecraft from the Nanorover, the launch vibration environment, and the free-fall and impact method for getting the Nanorover onto the surface of the asteroid. Along with the system constraints, the thermal environment of the asteroid posed a significant challenge for the Nanorover hardware. The thermal environment, coupled with the mass requirements, were the major driving requirements for the Nanorover design. These two requirement constraints, together forced the use of some unusual solutions in the design of the Nanorover components.

<u>Mass and Volume</u>

Due to the significant mass constraints on the MUSE C mission, the Nanorover and all of its launch retention, deployment, communications, and processing support equipment on the spacecraft was given a mass requirement of no greater than 3.5 kilograms. This mass was allocated as 1.7 kilograms for the Nanorover and 1.8 kilograms for the Orbiter Mounted Rover Equipment (OMRE). These mass requirements for the mission led to the optimization of every component of the Nanorover and OMRE for mass.

The volume requirements on the spacecraft were limiting in all directions. The spacecraft internal components and external electronics assemblies limited the Nanorover and OMRE in five directions. The spacecraft's stowed solar panels limited the Nanorover in the sixth direction and included a large dynamic envelope for the spacecraft's solar panel motion during launch. The zero gravity release and separation of the Nanorover from the MUSES C spacecraft were the source of additional functional requirements. The most notable requirement was the velocity of the Nanorover at separation had to be within a tight tolerance region. Too slow and the Nanorover would not be far enough from the spacecraft to be safe from the engine plumes. Too fast and the Nanorover could skip off the surface of the asteroid and go into orbit. These requirements had a significant impact on the volume of the final OMRE and Nanorover designs.

The Temperature Environment

The asteroid for the MUSES C mission rotates at a period of about 19 hours and experiences temperature variations at the surface from -160°C to +110°C. The large temperature swings at the surface are a function of the amount of dust covers the surface. It does not take much dust to insulate the body from the external environment. The dust also has very little heat capacity, resulting in the full temperature variation in a very short time frame when the surface goes from day to night or night to day. The quick temperature change and the large temperature range are very similar for any small body with a layer of dust.

The Vibration Environment

The vibration environment for low mass items can be very harsh. Since a low mass component likely has a high natural frequency in its assembly, the response to a random vibration environment can result in very high accelerations. Force limiting during vibration testing, a technique that utilizes the characteristic that items will not respond to high frequency accelerations because their mass filters out the high frequency components, is not applicable for low mass items. The transmitted accelerations that many of the Nanorover components responded to, and had to be strong enough to handle, were above 200 g's. The magnitude of the Nanorover random vibration test environment was 32 g's RMS. Small mass systems respond to the high frequency components of the vibration environment as well as the acoustic portion of the environment. Both sources of vibration generate significant loads on the small components that make up a small mass system. The vibration and acoustic induced loading drove all of the Nanorover component designs.

Electronic board assemblies contain electronic components on the circuit boards that are small and low mass. Electronic assemblies also generally contain several energy dissipative materials in their design to meet the needs of the electrical design. This situation results in the electronic assemblies usually not responding significantly to the high accelerations from vibration or acoustic sources. Most moving mechanical assemblies and structural components do not inherently contain significant amounts of energy dissipative materials. As a result, the components and structure are exposed to very high accelerations in a random vibration environment.

The Nanorover Design

Thermal Control for the Nanorover

The thermal control system for most spacecraft uses various methods to control the temperature and the thermal variations of regions of the vehicle where thermally sensitive components are mounted. The electronics bays, as an example, are one area where the control of the temperature is extremely important for the functional life of the electronic components as well as the thermal cycling life of the electronic packaging. Typical thermal control methods employ the use of thermal blankets, heat sources, heat absorption devices, thermal conductive paths to get the heat to the rejection surfaces, and radiators to reject the heat to the external environment.

The Nanorover presented a significant challenge in the thermal control design. The vehicle has very little external surface area due to its small dimensions and it is solar powered. Since it is possible for the Nanorover to be in any orientation with respect to the sun (including upside down), the Nanorover needs solar cells on all of its sides that could possibly face the sun in order to maintain power to the computer and actuators. This resulted in the entire available area on the top, bottom, front, and back to be populated with solar cells, as can be seen by the blue surfaces in Figure 1. Since the solar cells used nearly all of the external area available, there was very little space left over that could be used for heat-dissipating radiators. Another thermal control problem that a rover faces is the intimate thermal "contact" with the surface of the planet, comet, or asteroid. This condition leads to additional thermal control system design constraints.

The small internal volume of the Nanorover and the tight mass constraints led to a completely passive thermal design. There was no space in the vehicle to place batteries, heater units, or thermal switches and the free volume needed for thermal blankets was not available. The only location that a radiator could be placed on the vehicle was the two side panels that support the wheels, struts, and shoulder assemblies. The close proximity of the asteroid surface to these side panel radiators resulted in a heat input from the asteroid to the Nanorover for most of the daytime functional period. A balance was struck between improving the heat rejection to slow the temperature rise-time during the daytime operational period and reducing the heat rejection to keep the lowest nighttime temperature within a reasonable bound.

This balance was accomplished with several internal passive features of the rover design. To minimize the heat input from the solar panels during the daytime, the panels are thermally isolated from the interior of the Nanorover. The electronics, mechanisms, and instruments are all thermally tied to the optical bench to maintain alignment and minimize thermal gradients. To handle the thermal load of the Nanorover's internal components, the optical bench uses the wheel struts and the side panels for heat rejection radiators.

In order to obtain an operational period that was long enough for the required science return, the instrument detectors had to be kept cool for a longer period of time than the optical bench. Since the instrument detectors are mounted directly to the optical bench, some form of additional heat capacity was necessary to slow down the temperature rise of the detectors as the Nanorover heated up during the day. The camera and IR spectrometer instrument detectors are mounted onto an assembly that uses a material phase change from solid to liquid to slow down the temperature rise of the detector. These phase change assemblies effectively increased the heat capacity of the detector by a hundred times. The final thermal design of the Nanorover resulted in most of the components being exposed to a temperature cycle from -170°C to +110°C every 20 hours. Adding ±15°C margin for testing, the design temperature was -185°C to +125°C. A plot of the temperature of various components of the Nanorover during a complete day/night cycle of the asteroid is shown in Figure 4.

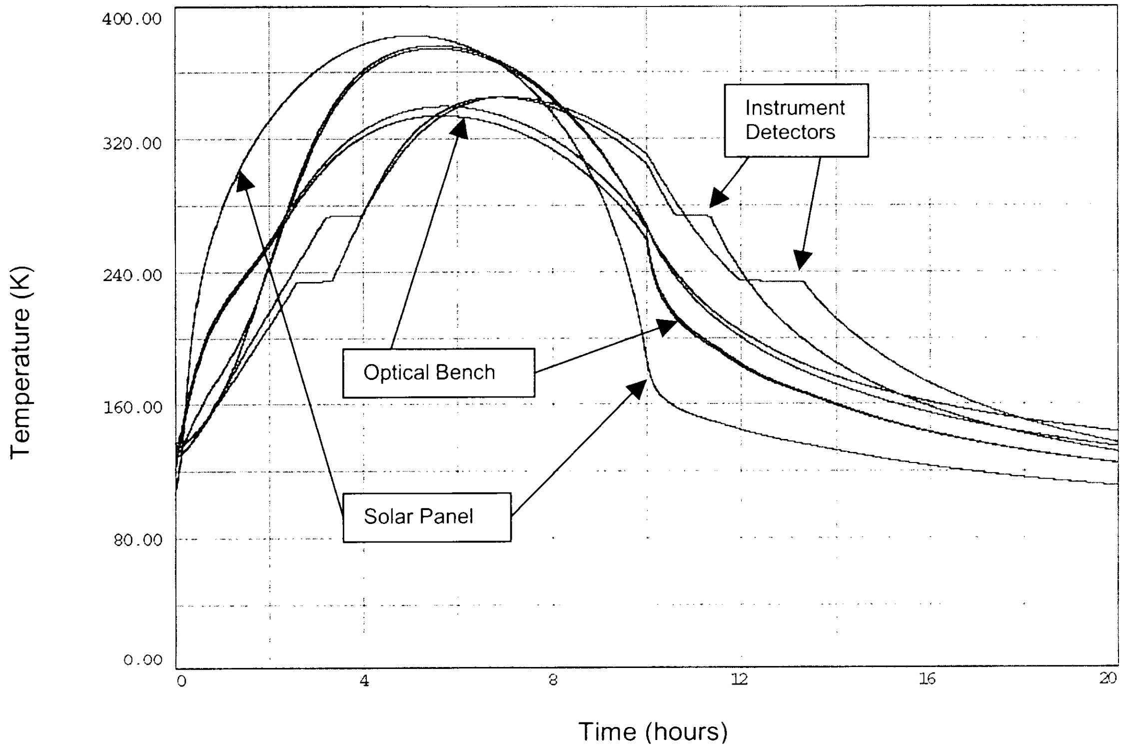


Figure 4. Nanorover Temperature Profile for One Day/Night cycle of 20 Hours

Mechanical Components

Nearly all of the mechanical components for the Nanorover are small, with the largest piece having dimensions about 20 millimeters in diameter. The camera barrel, which is athermalized over a 200°C temperature change, is shown in Figure 5 with a quarter for scale. The camera has a focus set to six meters in order to get appropriate blurring of stars to determine the location of the star's centroid. To image the surface of the asteroid, a two-meter focus is required. For close-up science data taking, a 70-millimeter focus is needed. To obtain these diverse focus requirements, a mechanism that moves a pair of lenses into and out of the optical path was developed. The mechanism, called the Loupe Mechanism, has three positions (lens1, lens2, no lens) and is shown in Figure 6 with a one-cent piece for scale. The largest components on the Loupe mechanism are about 10 millimeters in diameter and the smallest are less than one millimeter in diameter.

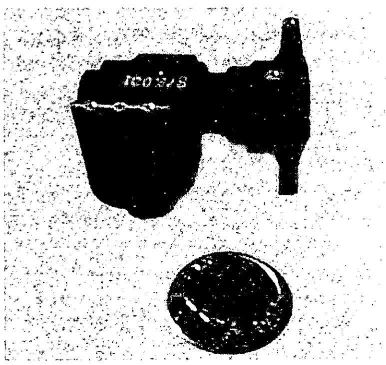


Figure 5. Camera Barrel with Optics Installed

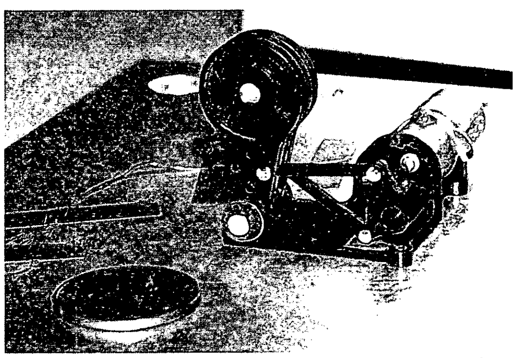


Figure 6. Loupe Mechanism on Vibration Fixture

The actuators developed for the Nanorover are 10 millimeter, brushless dc motors with a planetary gearbox. The actuators are capable of lasting over 100 million revolutions in a cryogenic environment. Rotor position sensing was not initially included in the motor design because back-EMF sensing for commutation was considered. Failure modes of the system led to the requirement for unpowered, static rotor position sensing of the motors and a hall sensor assembly was added to the motors. All of the motorized mechanisms (10 on the Nanorover and two on the OMRE) used this same actuator.

Nanorover Electronics

The electronics for the Nanorover are significantly more capable than the Mars Pathfinder Sojourner rover. While the Sojourner rover had batteries to keep the memory alive and the electronics warm throughout the night, the Nanorover has no space for such luxuries. When the sun goes down on the Nanorover, all functions cease. The Nanorover uses Electrically Erasable Programmable Read Only Memory (EEPROM) to store all of its code and overnight variables. Any data collected during the day must be downloaded to the MUSES C spacecraft or lost. The electronics also contains a large gate array that performs many of the hardwired functions. These functions include communications decoding, motor commutation and control, data routing and switching. The electronics system also contains an analog signal chain that provides the Analog-to-Digital conversion of the instrument data, temperature data, and engineering telemetry. Additional functions of the electronics system include power conditioning, power distribution, and motor drive amplifiers.

Since the Nanorover starts functioning as soon as the sunlight on the solar panels is sufficient to initialize the computer, the electronics assembly has to operate at the temperature extremes of the Nanorover components. The selection of electronic components that will function properly at the temperature extremes is very limited. The cold extreme is the defining temperature. None of the suppliers of the electronic components would rate their devices at the low temperature, so a large amount of testing was required to identify electronic parts that would properly function at -185°C.

The electronics system was allocated a very small volume in the Nanorover on one side of the optical bench. The large range of functions combined with the small available volume led to an electronic packaging design based on chip-on-board technology. The circuit boards are made from standard polyimide-glass material. The silicon is mounted directly to the polyimide boards and bond wires are routed from the pads on the silicon chips to pads on the boards. This method eliminates the additional part package normally used in standard electronic packaging designs. The major benefit for the Nanorover was a significantly reduced volume for electronic components and, because less board area was required, significantly reduced mass for the assembly. The most common method of protecting the chip-on-board assembly is to cover all of the integrated circuits and their wires to the circuit board with a polymer covering. The polymer has the same mass as the board material (sans copper) and represented a significant mass increase. The final design used the chip-on-board assembly without the polymeric covering, leaving the 0.1-millimeter diameter bond wires exposed. This approach required the use of handling fixtures due to the fragile nature of the assembly prior to completion of the final assembly.

The chip-on-board assembly packaging technique also met the large temperature range requirements of the Nanorover component assemblies. In addition to surviving the temperature extremes, the packaging design also survived the thermal cycling requirement of 100 cycles of the full temperature range.

The Nanorover System Mass and Design Maturity

The MUSES C mission, like most space missions, is very tight on mass margin. From the beginning of the Nanorover project, it was understood that mass would be very precious. The Nanorover project utilized the standard margin policies as outlined in AIAA specification number G-020-1992, titled "Guide for Estimating and Budgeting Weight and Power Contingencies for Spacecraft Systems". This specification recognizes that the smaller the mass of the finished system, the higher the mass margins need to be at various stages of the project. A plot of the AIAA recommendation for mass margin as a function of the stage of the project completion is shown in Figure 7. The recommendations are divided into four groups based on the system mass. The figure shows the values for Class 1 system designs only.[2]

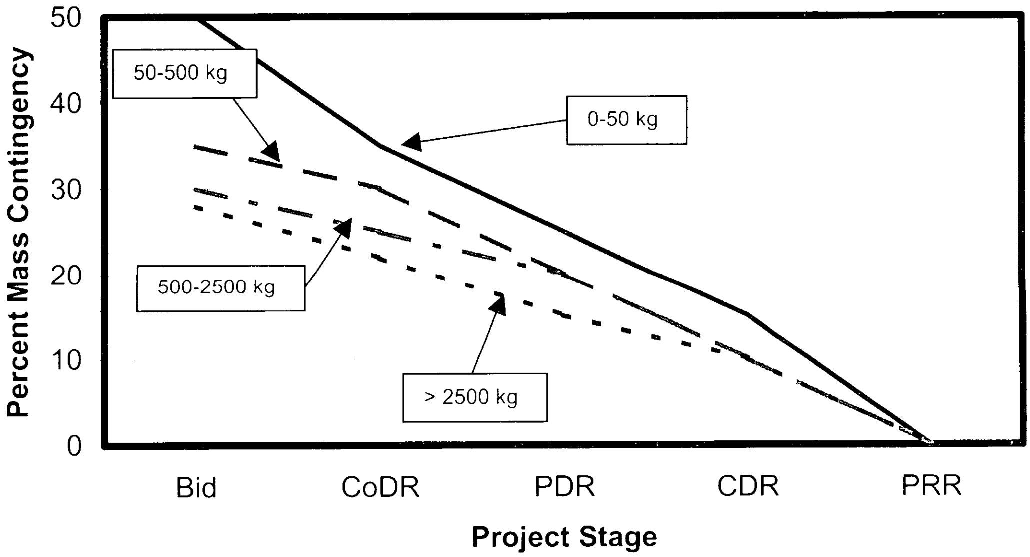


Figure 7. Mass Contingency Recommendations versus Project Stage[3] from AIAA G-020-1992 for Class 1 System Designs Only

Every detail of the Nanorover design was optimized to minimize the mass of every component. The motors have a mass of 3 grams and the gearboxes have a mass of 7 grams. The wheel assemblies with their proximity sensing capability weigh in at 20 grams. The camera barrel and optics have a mass of 137 grams. The gimballed mirror for the optical path was designed utilizing a Helmholtz coil arrangement, a beryllium mirror, and jeweled bearings to minimize its mass of 24 grams [1]. The Infrared Spectrometer's mass is 90 grams and the Alpha/X-Ray Spectrometer has a mass of 95 grams.[4]

As the design matured, the mass grew but the relative magnitude of the growth was much greater than expected. Figure 8 shows the Nanorover mass history as the design progressed from the Preliminary Design Review (PDR) to the Critical Design Review (CDR) for various components. In nearly every case, the assembly masses would increase dramatically in the beginning of the design as all of the functions were incorporated into the detail parts. The next phase of the design was a mass reduction effort that

[2] The AIAA specification defines a Class 1 system as "A new design which is one-of-a-kind or a first generation device". The AIAA specification has recommendations for systems of different levels of maturity. This paper only addresses the Class 1 category.

[3] Project stage definitions are: Bid = Proposal, CoDR = Conceptual Design Review, PDR = Preliminary Design Review, CDR = Critical Design Review, PRR = Preshipment Readiness Review.

[4] This is a partial listing of the Nanorover components only.

maintained the functionality of the assembly while reducing the mass. Typically, the final assembly mass would then rise a small amount as the components were manufactured and measured for mass.

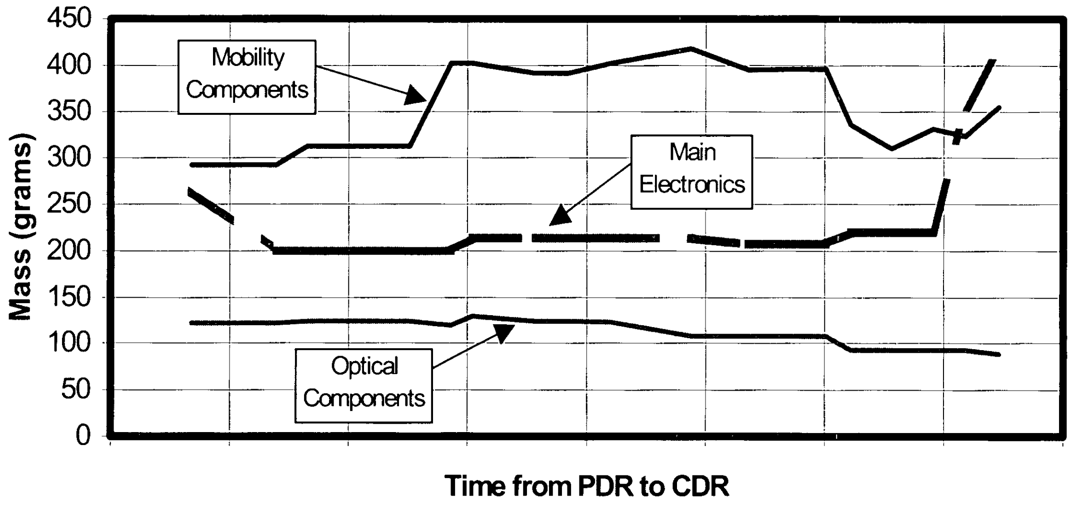


Figure 8. Selected Nanorover Component Mass History

The electronics assembly had a different history than most of the other components. The design mass dropped after the initial estimates as some of the circuitry was reduced and consolidated into a gate array. The next phase of the electronics design determined what components could be used in the thermal environment of the Nanorover. This resulted in several of the components being removed and replaced, often with more components or additional circuitry. Once all of the components were verified to operate at the thermal extremes, the final circuit and packaging design was completed. The large growth at the approach to CDR is due to several chip-on-board packaging details that were not accounted for in the original packaging plan. Figure 9 shows the mass history of the entire Nanorover assembly from PDR to CDR. The effect of the electronics assembly growth near the CDR is evident in the assembly history, even though other component groups were going down in mass.

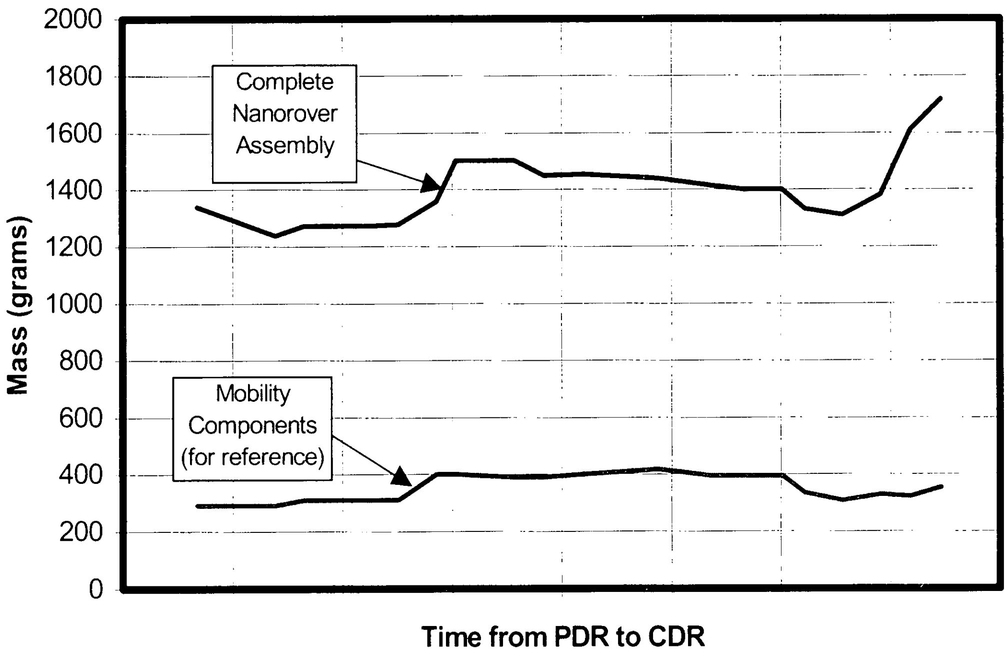


Figure 9. Complete Nanorover Assembly Mass History (Mobility Components History included for reference only to Figure 8)

Lessons Learned

Upon a detailed inspection of the trends, the normal mass margins that were planned for at the outset were very inadequate. The expected growth for a small mass system needs to be much greater than the AIAA specification suggests. The lowest mass range of the specification is from zero to fifty kilograms (see Figure 7). This range needs to be broken into smaller groups, with the lowest range being from zero to five kilograms. Note that five kilograms for the high end of the range represents the mass of the completed system with contingency. Several examples of the reasons for the large percentage mass growth on the Nanorover are listed below:

1. The motor assemblies were completed at a mass of three grams. When the need for the unpowered and static rotor position sensing was identified, a Hall sensor assembly was added to the motors. The sensor assembly mass was also three grams, or a 100% mass growth for the motors. This condition would never be the case for a typical sized motor around 25 millimeters in diameter. The motor mass would be about 100 grams and the addition of a sensor assembly would add around 5% to the motor mass.
2. The addition of the rotor position sensing on the motors increased the cabling to the motors by 200%. This was a mass increase of 90 grams to the Nanorover system (or the equivalent of an entire instrument).
3. The gearbox assemblies had an early mass of 4.5 grams. The mobility system design matured to require the gearbox output shaft to carry a moment load of 1.2 N•m. This change required an additional output bearing to carry the moment load. The mass increase was 2.5 grams, or a 55% increase.

4. The wheel assemblies with the proximity sensing capability built into the structure of the wheel had a mass of 20 grams. As the electronic design matured, three additional wheel-mounted electronic components were required to improve the resonant performance of the driving circuit. The three component masses are 1.2 grams in total, but the required addition of a small circuit board, supports, and capacitive coupling across the rotating interface to the wheel added 18 grams. This was a 90% increase in the wheel mass and it is multiplied times four for the Nanorover system.
5. The electronic circuit design was very sensitive to the components that could be found that would operate at the extreme cold temperature. Some of the components required additional support parts to perform the needed function. As electronic parts were identified that would function as required at the temperature extremes, the component count grew.
6. The quantity of memory required for a system is a function of the amount of software code required to perform the system functions. As the system design matured, the memory quantity requirement grew accordingly. This was very significant because the memory chips, even in silicon only, are very large. The radiation hard memory silicon is 1/3 the size of the Central Processing Unit. When another bank of memory chips were added, eight additional chips were required.
7. The biggest vulnerability to mass increase is in the electronics system. While any individual component is extremely small mass (especially with silicon chip components), the additional circuit board area required to mount the component and route the circuitry is the driving mass increase. As the electronic circuit design matured for the reasons stated in numbers 5 and 6, the required board area grew significantly. The use of chip-on-board packaging technology reduced the electronic assembly mass from 1.4 grams per square centimeter for standard packaging to 0.5 grams per square centimeter. The increase in area of the electronic assembly due to design maturity resulted in a 108% increase in its mass.
8. Another factor affecting the final system mass is the machining tolerances on the various components. While a typical component mass will match the CAD models by about one to two percent, the tolerances used on extremely small parts cannot expect the same result. The tolerances on the Loupe mechanism components are 0.05 millimeters. This tolerance represents 10% of the basic dimension. On typical parts, the tolerances are less than 1% of the basic dimension. This situation results in a greater variation of the final machined component from the design value. In one particular case on the Nanorover, the material used is Beryllium. Due to the high cost of the material, its brittle nature, and to minimize the risk of scrapping the part, the machinist made the parts at the maximum material condition of the tolerances on the entire part. The resulting component mass arrived 20% higher than the design value.
9. The use of fasteners must be considered early enough to obtain the desired size. Often, the required size for a fastener from design load considerations is not a standard size in the small fasteners. The use of larger than needed fasteners is very taxing on the system mass for small assemblies. As an example, the use of a #2 fastener (the Nanorover used English fasteners) over a #0 fastener is a mass increase of 105%. Going to the next standard sizes of a #4 over a #2, the mass increase is 70%. At the larger scales, a #10 fastener has a mass that is 34% greater than a #8 fastener, for the same length. The metric group of fasteners exhibits a similar trend. Fastener changes as design maturity occurs in a small system design can cause significant mass increases over the same types of changes in larger hardware.

Conclusions

The design of small spacecraft systems or components requires additional attention to issues that normally do not significantly affect larger devices and assemblies. The maturity of a flight design almost always results in mass increases for any system. Small systems are more sensitive to the maturity changes that occur in the normal design cycle than larger systems.

To begin with, a certain percentage of a very small mass is not very much in absolute value. Additionally, the growth of component masses as the detail design progresses is often a significant percentage of the initial value.

Machining tolerances for extremely small components cannot be maintained at the same relative magnitude as they can for larger parts. This can result in the final machined components having a large variation from the CAD system design mass.

The thermal environment and thermal control design may often lead to a large temperature swing in a small system. The internal heat capacity of a small system is low because there is little mass. The internal volume will often not allow the use of standard thermal control devices. This situation may be mitigated in the future as smaller thermal control components become available for spacecraft use.

The vibration environment for small components can drive the design significantly due to the component's tendency to respond to higher frequencies in the random vibration spectrum. The vibration response of the components can lead to large displacements that often cannot be tolerated. The addition of features to reduce displacement magnitudes or to maintain material stresses within allowable ranges will require additional mass. This additional mass in a small system can be disproportionately higher than a larger system because the accelerations and loading are markedly higher.

The electronic system mass in a small system is very sensitive to changes in the circuit design. Small changes in the component count add significant mass due to the additional needed circuit board area. If the thermal environment is as extreme as the Nanorover requirements, additional time and mass margin need to be added to allow for the identification of the electronic components that will function at the temperature extremes of the assembly. The determination of the components that will meet the functional needs of the electronics subsystem must occur very early in the project to prevent significant late mass growth that will affect the entire system.

The mass contingency plans on projects with a small system mass need to be greater in the early stages to account for the many items that will cause a large percentage growth of the system mass. Figure 10 shows a recommendation from this author for a modification to the AIAA specification and Table 1 lists the same information in tabular form. The smallest mass grouping for estimating should be zero to five kilograms. Future data from programs with masses in the range above five kilograms may indicate that there needs to be additional mass groupings between five and fifty kilograms. The design of small spacecraft systems or components requires additional attention to the issues listed above that do not significantly affect larger devices and assemblies. Small systems are more sensitive to the maturity changes that occur in the normal design cycle than larger systems. The recommended specification modification in Figure 10 provides the mass growth capability needed for small system designs.

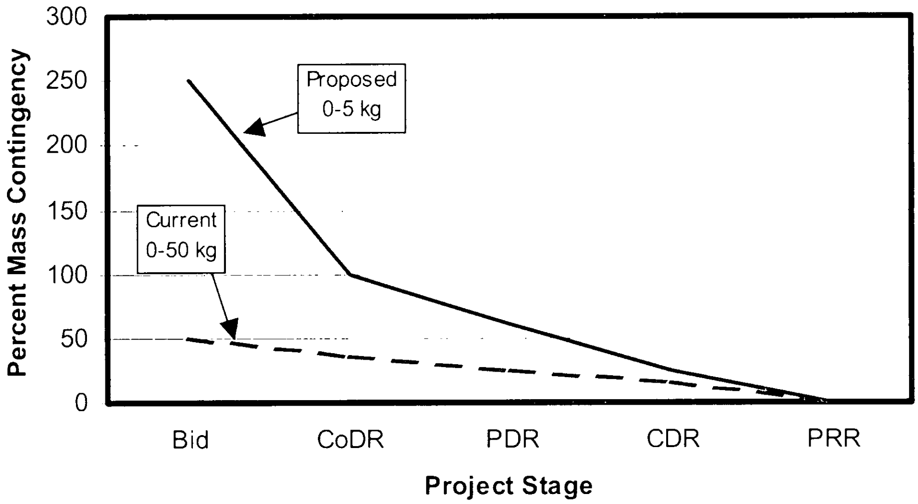


Figure 10. Recommended Modification to the Low Mass Group For Class 1 System Designs of AIAA Specification G-020-1992

Table 1. Recommended Modification to the Low Mass Group For Class 1 System Designs of AIAA Specification G-020-1992

Project Stage	Percent Mass Contingency
Bid	250
CoDR	100
PDR	60
CDR	25
PRR	0

References

1. Boz Sharif, Ed Joscelyn, Brian Wilcox, and Michael R. Johnson "Development of a Miniature, Two-Axis, Triple-Helmholtz-Driven Gimbal" *34th Aerospace Mechanisms Symposium*, (May 10-12, 2000), pp. 189-198.

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