Developing Tools for the Study of a Mars Sample Return Orbiter
And
Creating Realistic Renderings of a Mars Ascent Vehicle

JPL Internship Final Paper

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Abstract

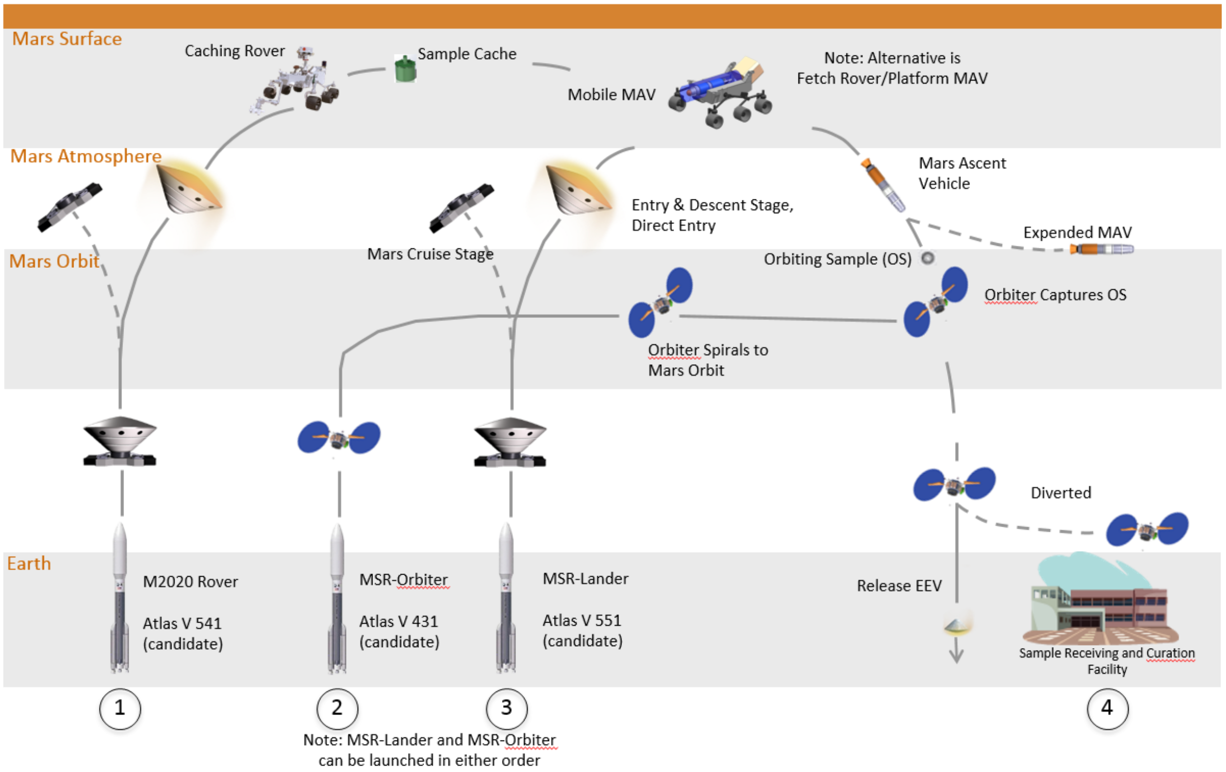
The proposed Mars Sample Return mission architecture envisions a sample return orbiter utilizing solar electric propulsion (SEP). To facilitate studies of low thrust SEP missions a tool has been developed, referred to as MORT, that selects trajectories and estimates spacecraft mass based on a set of mission parameters. This summer improvements have been made to this tool on many fronts, including improved models of the attitude control subsystem and monopropellant propulsion system, a method for estimating moment of inertia, mass estimates of individual components, and programmatically generated interactive html outputs. For each subsystem data was analyzed, correlations between performance and mass identified, and methods developed to estimate the mass of each component. Moments of inertia were estimated by modeling the notional spacecraft as simply a cubic bus with two solar arrays. Component level mass estimates were created by adding information already calculated within the model to the output. Finally, the data print-out was created by generating html directly from the Matlab model, and displaying it in Matlab's built in browser. These efforts have increased the accuracy and fidelity of the model, as well as the ease of access to the data that the model produces, and will contribute to future trade studies for the many orbiter concepts being considered.

A second element of Mars Sample Return under study is a Mars Ascent Vehicle, or MAV. One necessary element of the study is to generate image and visualizations. Realistic renders have been made of the MAV in multiple environments, using NX's rendering functionality and CAD models developed as part of the study. For each model materials, shadows, backgrounds and more were chosen to create a realistic appearance, and a number of images were created. Additionally, a guide to NX Rendering has been written, for future users of the software to learn how to use generate basic renders quickly. The guide has been provided to the MAV team and uploaded to JPL Wired. Finally, several diagrams of the propulsion system have been produced using Microsoft Visio, and provided as reference material.

I. Potential Mars Sample Return Architecture

Mars Sample Return is a potential campaign of three missions with the aim of returning samples from the surface of Mars to Earth. First, the Mars 2020 rover would collect samples and leave them in caches on the surface. Next an orbiter, known as a Sample Return Orbiter (SRO), would travel to Mars orbit and stay there for up to a decade. It would be a vital telecommunication asset, and possibly perform science as well. The third and final mission would be the Sample Return and Launch (SRL) mission. A lander would collect the samples left on the surface by Mars 2020, and launch them to Mars orbit in a rocket called a Mars Ascent Vehicle (MAV). An SRO would then rendezvous with the samples in orbit then return them to Earth. The samples would be returned no earlier than 2031 in the current timeline.

Mars 2020 is well into development and on track to launch during the 2020 opportunity. The other vehicles in the proposed architecture, an SRO, an SRL lander and a MAV, are under study currently by the Mars Advanced Studies Team. The studies contributed to this summer were a MAV and an SRO.



The proposed MSR architecture

II. MORT Introduction

The current concept uses solar electric propulsion (SEP) for the orbiter. SEP trajectories are considerably more flexible than chemical trajectories, and trajectory options are tightly linked to the mass, power, and propulsion capabilities of the craft. As a result the trade space is complex, coupled, and multidimensional.

To facilitate various orbiter studies, the Mars Advanced Studies Team has developed a tool known as the Mars Orbiter Tool, or MORT. MORT is a Matlab script that takes a set of mission parameters including Earth departure and return dates, orbits to visit at Mars, solar array and thruster details, carried and picked up mass, and several others. Based on these parameters MORT iteratively estimates the mass of a spacecraft that would be necessary, and selects a matching and feasible trajectory from a database.

Several projects have been underway to improve this tool in various ways. A new output was created, new output data structures implemented, two of the subsystem models rewritten, and a method to estimate spacecraft moment of inertia created.

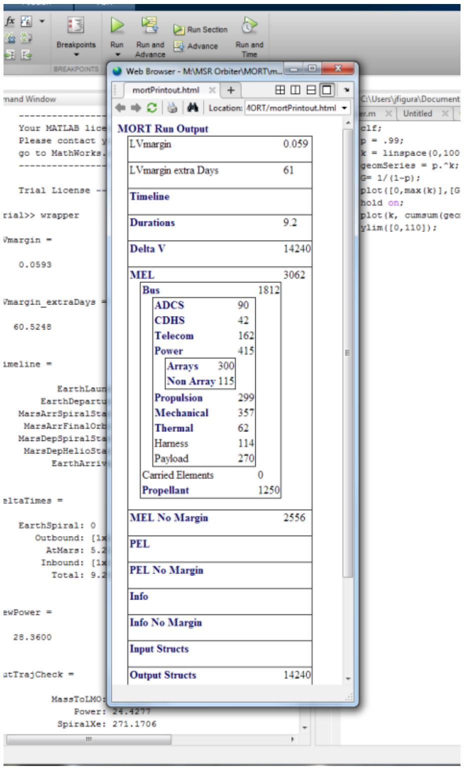
III. MORT Printout

The first project was to improve MORT's output formatting. At the beginning of the summer the output consisted of lines of variables printed to the Matlab command window. This was the primary method for viewing the output, and the only way to share the information generated by the program with non-MORT-users. The objective of the printout project was to create an improved output, one that would be simple to read, easy to use and easy to share.

The approach chosen was to write the results of the MORT run to an html file. HTML was chosen because of the flexibility that it offered, the ability to incorporate simple scripts, the ability to use Matlab's built in browser to display the results, and the ability to easily share the results with non-MORT-users.

MORT Printout goes through a structure recursively and generates an html version of the information. It places the contents of the structure and all of its substructures into an html table or list, in the form of a long string of characters. It automatically formats variable names, fixing capitalization and adding spaces. The program is coded to handle any structure, regardless of what the field values are, so if the output is changed in the future MORT Printout will work without alteration. After being generated, the printout is displayed in a pop up window in Matlab's built in browser.

Additionally, the program incorporates JavaScript to expand and collapse elements in the output. Every variable that is a structure can be expanded, showing its sub fields and their data. This allows very large structures to be included in the output while still being accessible.



```
MORT Run Output
  LVmargin                  0.059
  LVmargin extra Days       61
  Timeline
  Durations                 9.2
  Delta V                   14240
  MEL                       3062
    Bus                     1812
      ADCS          90
      CDHS          42
      Telecom       162
      Power         415
        Arrays      300
        Non Array   115
      Propulsion    299
      Mechanical    357
      Thermal       62
      Harness       114
      Payload       270
    Carried Elements        0
    Propellant              1250
  MEL No Margin             2556
  PEL
  PEL No Margin
  Info
  Info No Margin
  Input Structs
  Output Structs            14240
```

An example printout, in the Matlab window

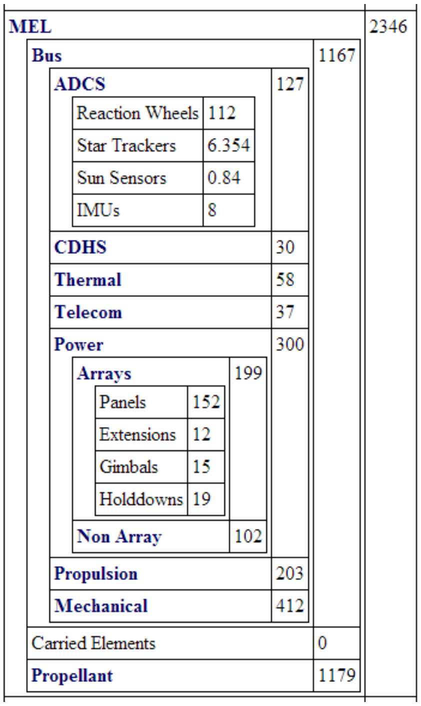
The new printout function has improved the accessibility of the wealth of information that MORT generates, and is a good first step in improving the tool.

IV. Revised Output Structure

At the beginning of the summer MORT outputted an assortment of variables, including a subsystem level mass budget, a timeline, margins, and more. The output variables were sufficient, but improved fidelity and formatting was desirable. The MORT team decided to implement several new output structures to improve the organization of information, and to add component level detail to the model.

Note the difference between this project and MORT Printout: The printout function is called after a MORT run, and formats whatever structure is outputted. This project is aimed at changing the actual structure that the model produces, reorganizing the information rather than the formatting of the output display.

In the revamped output, there are three primary output structures. The Master Equipment List (MEL) lists every subsystem and component, with mass estimates for each. The Power Equipment List (PEL) will list power required to each subsystem and component; it has not yet been populated. Finally, Info lists parameters, assumptions and other miscellaneous information for each subsystem. All three have margined and unmargined versions.



MEL					2346
	Bus				1167
		ADCS			127
			Reaction Wheels		112
			Star Trackers		6.354
			Sun Sensors		0.84
			IMUs		8
		CDHS			30
		Thermal			58
		Telecom			37
		Power			300
			Arrays		199
				Panels	152
				Extensions	12
				Gimbals	15
				Holddowns	19
			Non Array		102
		Propulsion			203
		Mechanical			412
	Carried Elements				0
	Propellant				1179

A partially expanded MEL in the MORT Printout

Populating the MEL was the most important task. It was done differently for each subsystem. For the subsystem models being reworked, the new models were designed to calculate the mass of each component individually (more on that below). Some subsystems already calculated component masses, such as Telecom, and the new outputs were implemented using the information already available. Finally, a few subsystems didn't have component level detail, like Thermal. For these, a placeholder component equal to the total subsystem mass was put in and will be updated in the future by the orbiter team.

The new outputs structures present the results of a MORT run in a clean and detailed fashion. They will be the bread and butter of MORT going forward.

V. ADCS Model

Mort uses a set of smaller scripts to generate mass estimates of each subsystem. Mass estimates are produced iteratively, by repeatedly running the script until the result converges. In each iteration the total spacecraft mass estimate is produced by summing the results of the subsystem models. Two of these models were rewritten this summer, beginning with the Attitude Determination and Control Subsystem (ADCS) model. The old model produced a total subsystem mass as linear function of the wet mass only. The goal for the new model was to be more accurate, to scale more accurately, and to specify the mass of each component as well as the total system mass.

The typical components of an ADCS system include thrusters, reaction wheels and sensors. Attitude control thrusters are handled in the propulsion subsystem. Reaction wheels are massive wheels spun at high rpm. By altering the speed of the wheel one can control the rotation of a spacecraft. The sensors commonly used for interplanetary missions include sun sensors, star trackers and IMUs. Star trackers determine attitude by comparing the visible star field to a database of star fields. Sun sensors detect the presence of the sun in their field of view to ascertain attitude. IMUs use a combination of accelerometers and gyroscopes to determine attitude without reference to external information.

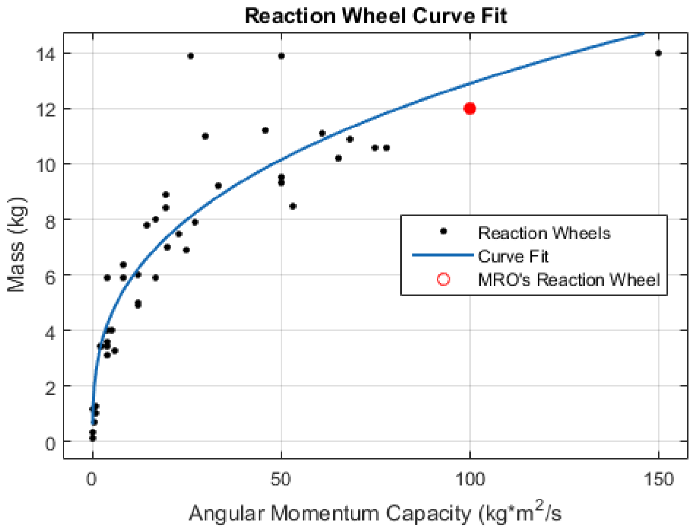
Models for each component were developed by referencing a spreadsheet provided of components and their properties. From this spreadsheet, appropriate performance metrics were chosen and compared to mass. Various methods were used to size the different components, detailed below. The model estimates component mass as a function of spacecraft mass, moment of inertia, and a sensor quality parameter, which can be low, high or ultra-high. The total subsystem mass is the sum of each of the component models.

For many of these models, analogy to the Mars Reconnaissance Orbiter (MRO) are used because it is the historical mission most similar to the notional SRO.

A. Reaction Wheels

Reaction wheels are the heaviest component of the ADCS subsystem, and the most complicated system to size. The chosen performance metric for reaction wheels was the total angular momentum capacity. There was a strong relationship between reaction wheel mass and the momentum capacity. This was as expected; a more massive wheel will have a higher moment of inertia, and consequently be able to store more momentum.

From a database of commercially available reaction wheels, an equation for reaction wheel mass as a function of angular momentum capacity was generated using Matlab's curve fitting functionality. The curve fit is reasonably accurate across the entire range of reaction wheel masses in the data set.



The necessary angular momentum capacity was estimated as a linear function of the moment of inertia of the spacecraft being examined. The ratio of MRO's average moment of inertia to the momentum capacity of its reaction wheel was used to calibrate the relationship, as the slope of the linear function.

The moment of inertia estimation is done elsewhere in MORT. More information on that functionality is later in this report.

Four reaction wheels are used in all cases. One is for each principal axis, and one is redundant and skewed so as to be able to replace any of the other three. This number is the standard for interplanetary missions, and is used in all MORT runs that use the new model.

B. Star Trackers

Star Tracker mass was plotted against accuracy and against field of view, and no correlation was found in either. This makes a certain amount of intuitive sense: a star tracker's performance is based on its programming and electronics, neither of which are tightly linked to mass.

Because of the lack of correlation, the model uses the mass of the MRO star tracker. The quantity is also fixed at two; at least two are absolutely necessary for redundancy, and more is excessive. This is the standard for interplanetary missions.

C. Sun Sensors

Similarly to star trackers, there was no correlation between star tracker mass and accuracy or field of view. However, the number of sun sensors is much more flexible than the number of star trackers. Sun sensors are considerably lighter and lower accuracy, and the number used is determined by the design of the spacecraft.

The model uses the mass of the most massive MRO sun sensor (MRO used three types, each slightly different mass). The number used is determined by the sensor quality parameter. Low uses 4, high uses 8, and ultra-high uses 16. For reference, MRO used 16, but MRO used an unusually high number to help protect the sensitive camera equipment.

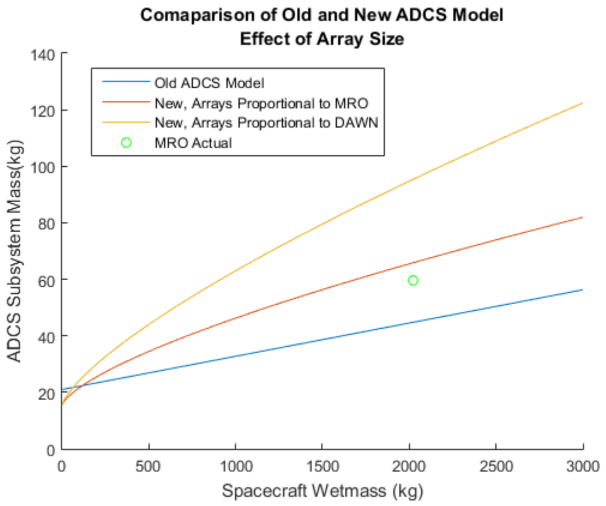
D. IMUs

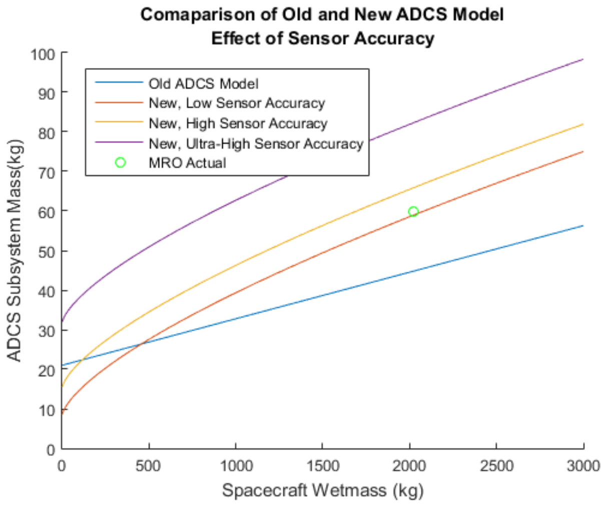
Unlike the other two sensors, IMU performance did correlate with mass. In the data examined there were two IMUs with TRL 9, one light and the other medium mass. Additionally there were two heavier IMUs, with correspondingly greater accuracy. The highest performing IMU was the heaviest, and the lowest performing was the lightest.

The model pins IMU mass to the sensor quality parameter. "Low" selects the lightest sensor, the Litton LN200s. High selects the medium mass IMU, the Honeywell MIMU YG9666B. Finally, ultra-high accuracy selects the Litton LN-100S

E. Conclusion and Future Work

It may be worthwhile to investigate large reaction wheels, as the notional SRO will likely be larger than MRO and use larger wheels. The data on reaction wheels in that region is scarce, so further investigation would be helpful to confirm the validity of the reaction wheel sizing approach. Additional work can be done investigating small sensors, such as those used for cubesats. The new ADCS model is least accurate for small spacecraft, where the constant values for sensors become a larger portion of the total mass.





VI. Monoprop Model

The notional SRO’s main propulsion would be SEP, but it would also have a secondary propulsion system for reaction wheel desaturation and for rendezvous maneuvers. The secondary propulsion system model (which will be referred to as the monoprop model) was also replaced this summer, with the same goals as the ADCS model: increase accuracy and add component level detail.

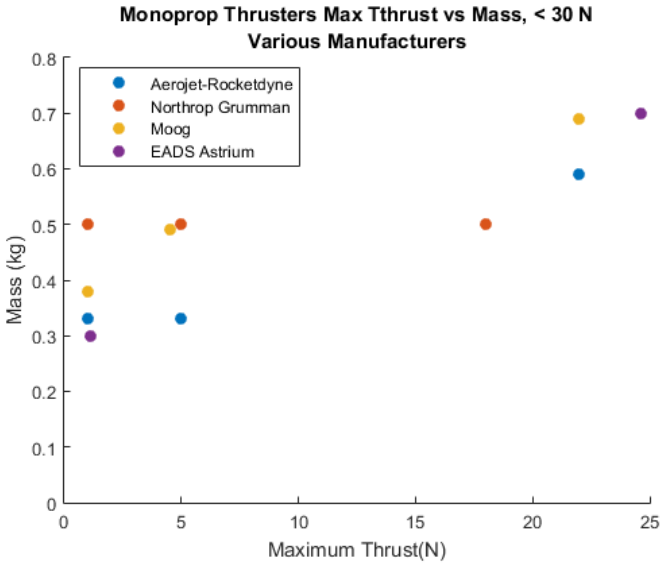
There are three possible systems: blowdown hydrazine, regulated hydrazine, or cold gas xenon. Blowdown hydrazine is sufficient when the volume of hydrazine is low, while regulated systems are superior for large quantities of monopropellant. Cold gas xenon has a far lower Isp, but is also non-toxic, and therefore likely cheaper. All three were modeled. The user may manually select any of the three, or may let the script automatically select the hydrazine system with the lowest mass.

The main components of the secondary propulsion system would be thrusters, tanks and plumbing. Blowdown systems would use only a hydrazine tank, regulated systems use both a hydrazine tank and a pressurant tank as well as a small mass of pressurant, and xenon cold gas uses a small plenum tank in lieu of the hydrazine tank.

A. Thrusters

Data was collected on monopropellant thrusters under thirty newtons from four manufacturers. Small monopropellant thrusters come in three thrust levels: one newton, five newton, and twenty two newtons (The thrusters are actually between 18 and 24 newtons, but they will be referred to as 22 N thrusters). Thrust and maximum throughput were compared to mass. There existed correlations between both.

It was decided to use a discrete model for thruster mass, rather than a curve fit because these sizes are standard across industry. The user chooses how many 1 N, 5N and 22N thrusters to use. The mass per thruster used is the average mass for that thrust category of the four manufacturers, and the total thruster mass is the sum of the number of thrusters times the mass per thruster for each thrust level.

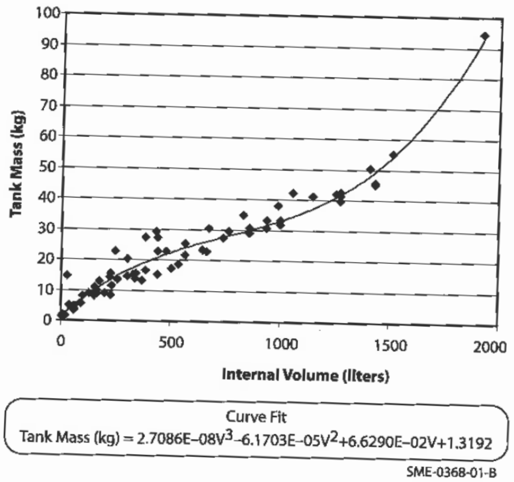


Three groupings are visible, around 1N, 5N, and 22N

B. Tanks and Pressurant System

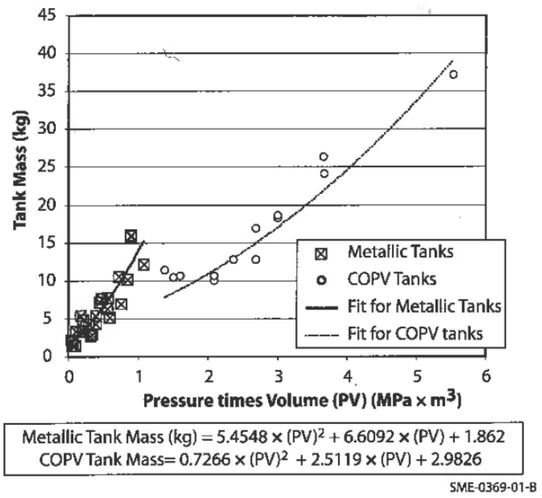
Hydrazine tank masses are calculated using a curve fit of tank mass as a function of volume from *Space Mission Engineering: The New SMAD*. For blowdown systems, tanks are sized to three times the volume of the hydrazine being stored. Regulated systems are sized to the volume of the hydrazine plus ullage space.

For regulated systems, the mass of pressurant needed is calculated using the ideal gas law, the volume of the tank being pressurized, the thruster inlet pressure and the tank starting pressure. The mass of the pressurant tank are calculated using a curve fit from SME from the pressurant mass and starting pressure.



Curve Fit
Tank Mass (kg) = 2.7086E–08V^3–6.1703E–05V^2+6.6290E–02V+1.3192

Fig. 18-9. Typical PMD Propellant Tank Mass.



Metallic Tank Mass (kg) = 5.4548 × $(PV)^2$ + 6.6092 × (PV) + 1.862
COPV Tank Mass= 0.7266 × $(PV)^2$ + 2.5119 × (PV) + 2.9826

Fig. 18-11. Pressurant Tank Mass as a Function of Operating Pressure Times Volume.

The Tank curve fits from SME. PMD Hydrazine on the left, pressurant on the right.

C. Plumbing

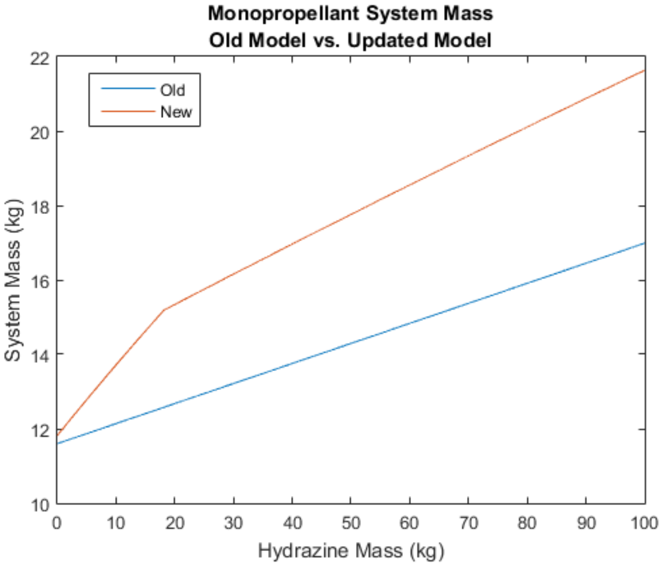
Sizing the plumbing was the most difficult part of developing the new monoprop model. The components of the plumbing vary greatly between systems and there was no obvious algorithm to size the plumbing.

Plumbing mass is estimated based on the number of thrusters. The current model uses an estimate of half a kilogram of mass per thruster, with the total plumbing mass being equal to the number of thrusters times 0.5. The rationale is that each thruster requires piping, valves, and other components, so the greater the thruster number, the greater the plumbing mass.

D. Conclusion and Future Work

The plumbing mass is the weakest part of the ADCS model, and the most in need of revision. Possible improvements include pinning plumbing mass to bus volume, rather than number of thrusters, or improving the estimate of mass per thruster.

The xenon cold gas model needs improvement. The value for the plenum tank used is a placeholder, and should be replaced if the cold gas model is used extensively in the future. Additionally, consideration should be made for performing reaction wheel desaturation with the main SEP system, as a way to reduce the demands on the R.C.S. thrusters.



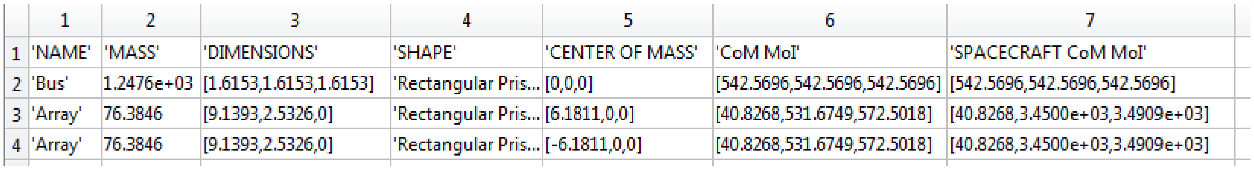
Comparison of models for hydrazine systems. Cold gas not included. The kink is the switch from blowdown to regulated.

VII. Mechanical Properties

It became apparent while writing the ADCS model that the moment of inertia of the spacecraft will become increasingly important. SEP spacecraft use enormous solar arrays to power the electric engines, and these solar arrays have a correspondingly large moment of inertia. It is possible that this notional SRO might have the highest moment of inertia of any interplanetary spacecraft, with the possible exception of the proposed ARRM vehicle. These high moment of inertias have serious implications for ADCS system sizing and for the maneuverability of the vehicle.

Because of these considerations, it was decided to add a mechanical properties module to MORT. The goal is to estimate the moment of inertia of the spacecraft concept generated in each run, from only the spacecraft mass and the few component properties known.

This was accomplished by creating what is essentially a barebones CAD program. A user models a set of entities and inputs their positions, dimensions, shape and mass. The script uses that information to calculate the center of mass and moments of inertia of each entity and the spacecraft.

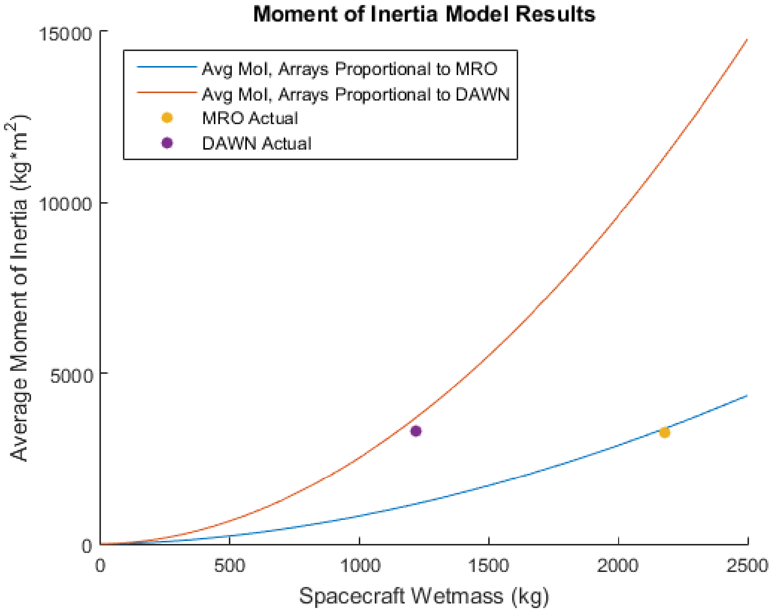


	1	2	3	4	5	6	7
1	'NAME'	'MASS'	'DIMENSIONS'	'SHAPE'	'CENTER OF MASS'	'CoM MoI'	'SPACECRAFT CoM MoI'
2	'Bus'	1.2476e+03	[1.6153,1.6153,1.6153]	'Rectangular Pris...	[0,0,0]	[542.5696,542.5696,542.5696]	[542.5696,542.5696,542.5696]
3	'Array'	76.3846	[9.1393,2.5326,0]	'Rectangular Pris...	[6.1811,0,0]	[40.8268,531.6749,572.5018]	[40.8268,3.4500e+03,3.4909e+03]
4	'Array'	76.3846	[9.1393,2.5326,0]	'Rectangular Pris...	[-6.1811,0,0]	[40.8268,531.6749,572.5018]	[40.8268,3.4500e+03,3.4909e+03]

An example of the matrix used in calculations

The model currently in use includes only the bus and two arrays. The bus is assumed to be cubic and uniform and the arrays stand off a set distance. The user inputs the array dimensions and mass, the bus wet mass, and the distance between the edge of the bus and the edge of the array. The bus is assumed to be the density of the DAWN bus, and its dimension is calculated from that density and the wet mass minus the array mass. This modeling approach is accurate despite its simplicity: the code estimated MRO and DAWN inertias to within 15%. The model is accurate because for most spacecraft and especially for SEP spacecraft the moment of inertia of the solar arrays is far greater than the moment of inertia of the bus, so accurately modeling the solar arrays while assuming a uniform cubic bus is a sufficient approximation.

The mechanical properties program is designed to be easily extensible. A future user can add more entities, such as an antennae, and the program will automatically include them in the calculation.



VIII. MAV Concept Study Introduction

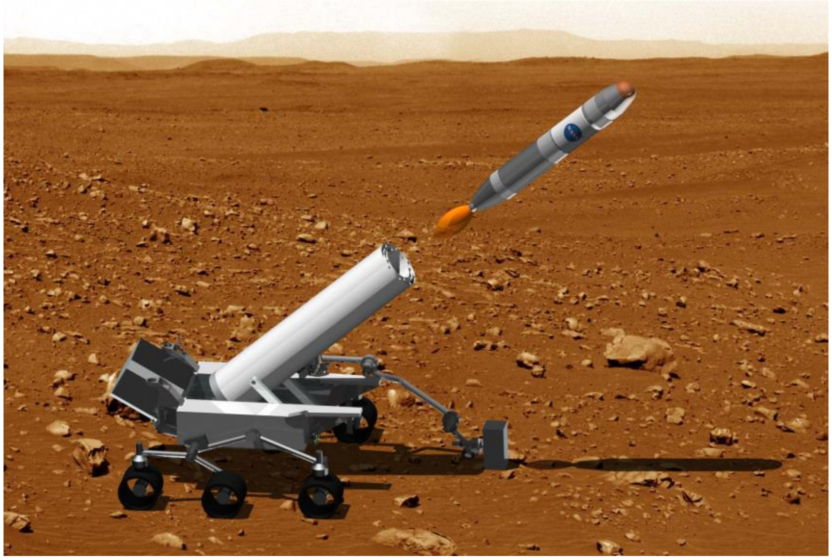
The MAV concept study is examining a range of possible designs and propulsion options for the ascent vehicle. The cases under consideration include solid, liquid and hybrid motors, and both spin-stabilized and thruster stabilized options. Elements of the study include generating MELs, CAD models, studies of propellants under extreme thermal conditions, mechanical analysis of the launch tube, CFD of rocket behavior in the Martian environment, and several more areas of investigation. The goal of the study is to develop high level designs for every viable case. These results will inform decisions for the direction of future study and eventually the design of a MAV.

IX. MAV Concept Renderings

One of the necessary tasks in the MAV study is to produce images and illustrations for presentations and reviews. One category of image is the artist's impression: an image that appears lifelike, rather than showing engineering information. These sort of images are necessary for reviews and presentations, including the end of year review, which occurs this fall. The goal of this project was to produce lifelike images of the MAV concepts under study in a variety of configurations, including a MAV being launched, a MAV in Mars orbit, and others.

To produce the images NX's built in rendering functionality was used. Each part was assigned a material, and the appearance tweaked until appearing realistic. A background image was chosen to make the model appear to be at Mars. Lights were set up to illuminate the model, and shadows configured. The model was oriented and a render made.

This was done for each arrangement mentioned above. Over seventy images were generated of varying quality, the best of which could be used in future MAV materials.



An example of the renders generated

X. NX Rendering Guide

Because the MAV concept study is ongoing and the models are subject to constant change and because this author’s internship is coming to a close, it was decided to write a short guide to NX rendering to facilitate future rendering creation. The available documentation on NX rendering is of variable quality, and can be difficult to find. The goal of the guide is to be accessible and quick, and to teach a new user the basics of the rendering functionality within a few hours. The images produced using NX rendering and a new user will not match those produced by a dedicated graphic design software, but will be sufficient for an evolving study.

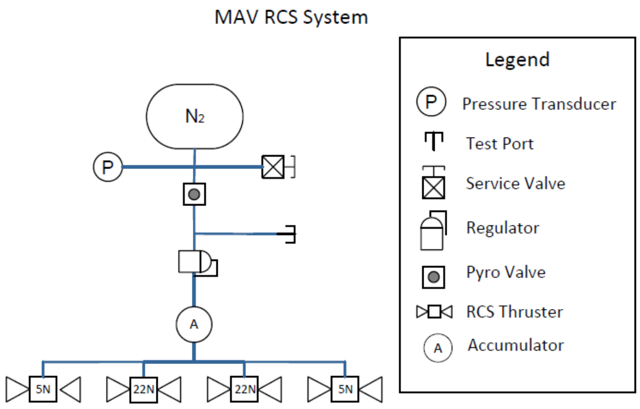
The result will be provided to the MAV team, for use if they choose to create updated models. It will also be uploaded to the JPL wired wiki, as a resource for future NX users.

XI. Propulsion Diagrams

The final task completed for the MAV group was creating diagrams of the propulsion systems of the various cases under study. As mentioned, there are multiple propulsion system options being considered, and each has its own configuration and plumbing. Diagrams were necessary to communicate the configuration information. Specifically, two liquid cases, a hybrid case and the R.C.S. system needed to be illustrated.

Microsoft Visio was used to create the diagrams. Visio is a software for creating flow charts and other illustrations. The configuration information was provided in handwritten diagrams. Based on these, computer diagrams were created and made neatly.

The diagrams made were provided to the team as reference material for future use.



An example diagram of a potential MAV concept RCS system layout. Used with the permission of Ashley Karp.

XII. Conclusion

This summer a number of tasks for the two studies have been completed. The internship was a productive and extremely educational experience, and I’m glad to have contributed to JPL and to the exploration of space.

XIII. Acknowledgements

I’d like to thank my mentors, Austin Nicholas and Charles Budney, for overseeing my work and providing information and support. Rob Lock and the other members of the orbiter team provided insights and comradery. On the MAV team, Robert Shotwell and Morgan Hendry were my primary contacts. Finally, I’d like to thank my cubicle-mate, Yoav Schoss, and the other interns I worked with this summer; Alexx Cisotto, Ash Das, Ben Migirditch, Bennet Kapili, and Austin Nicassio. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the JPL Summer Internship Program and the National Aeronautics and Space Administration.

XIV. References

Wertz, James Richard., David F. Everett, and Jeffery John. Puschell. *Space Mission Engineering: The New SMAD*. Hawthorne, CA: Microcosm, 2011. Print.

Mattingly, R. and Mays, L., “Mars Sample Return as a Campaign, Jet Propulsion Laboratory, IEEEAC paper #1805, 2011