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A MICRO NEWTON IMPULSE-BIT HYDRAZINE THRUSTER—DESIGN, TEST, AND MISSION APPLICATIONS

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A small thruster, that will herein be called the Hydrazine milliNewton Thruster (HmNT), has been designed and vacuum hot-fire tested, demonstrating a range of thrust and impulse far below the current state-of-the-art (SOA) hydrazine thruster. Steady-state thrust levels of 35–135 mN, and minimum impulse-bits of 25–120 μN-s were demonstrated over a typical operating range of inlet pressures. These capabilities provide new spacecraft and mission design options, including the following.

- Functional backup for Reaction Wheel Assemblies (RWAs), which can be used to prolong the useful life of RWAs
- RWA replacement for certain missions to save mass, power, and cost
- Precision delta-V that can be used for
  - proximity operations and docking maneuvers
  - formation flying
  - primary attitude control for SmallSats and CubeSats
  - primary delta-V for CubeSats

INTRODUCTION

Hydrazine propulsion systems are used on most spacecraft larger than SmallSats, and some in the SmallSat class. The current SOA hydrazine thrusters cannot achieve the milliNewton level thrust and microNewton level impulse required for precision pointing and precision delta-V applications. Spacecraft and mission designers have no practical options other than RWAs for precision

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pointing, and no functional redundancy for RWAs when jitter problems occur. Options for precision delta-V typically involve adding an additional propulsion system to the already existing primary propulsion system, which can be costly in dollars as well as systems resources. Electric propulsion thrusters can achieve very low steady-state thrust levels. However, with the exception of Pulsed Plasma Thrusters, most are not designed to deliver discrete small impulses, and electric propulsion systems are very costly. Other design choices for small impulse-bits include cold gas GN2, butane, ammonia, or similar fuels which have very poor specific impulse (Isp), and are prone to propellant leakage as are all propellants which are gaseous at the thruster valves. "Warm gas", i.e., gas generator systems can be scabbed onto an existing hydrazine system with plenum tanks and other components, however they can impose operational restrictions and also prone to gas leakage.

The HmNT was developed to provide a reliable, efficient, and cost-effective solution for precision pointing and precision delta-V applications. The HmNT can be easily added to standard hydrazine propulsion systems without the need for additional tanks, or propulsion components other than the thrusters themselves. This minimizes the impact on the spacecraft system resources and mission operations design. It was designed to work over the standard range of operating pressures, 689 kPa–2758 kPa (100–400 psia), which allows it to operate in a "blowdown" monopropellant system as well as pressure regulated mode. For all of the above reasons, our design choices were based on miniaturizing the elements of a standard hydrazine thruster. This paper will discuss the approach taken in the design and development, hot-fire test results, and mission applications.

DESIGN AND DEVELOPMENT

In order to meet the functional objectives stated above, studies[1] were conducted to consider how the HmNT would be used within existing spacecraft attitude control and propulsion systems, and how it would operate in conjunction with the conventional hydrazine thrusters needed to satisfy the larger thrust and impulse functions. A spacecraft will typically use 1 N, 5 N, or 22 N thrusters to rotate the spacecraft at a relatively fast rate during telecom turns-to-Earth, Sun-pointing, or a retargeting slew. In order to replace RWAs, the HmNT would need to reduce the residual rotation from these faster rate maneuvers to much slower rates required for precision pointing. It was determined that the HmNT would not only have to produce very small impulse-bits, (single short pulses typically called minimum ibits), but also be able to operate at full thrust in steady-state mode in order to handle these rate transitions. For reference, we will call these "fast-rate to slow-rate transitions".

These design studies resulted in two main technical objectives that guided the design:

1. Produce minimum ibits small enough to provide the precision pointing required to replace reaction wheels, and the capability for precision delta-V needed for proximity operations, docking, and formation flying maneuvers.
2. Operate in steady-state mode for several 10s of seconds, in order to handle the fast-rate to slow-rate transitions from larger thruster activities, to the lower rotational rates required for precision pointing.

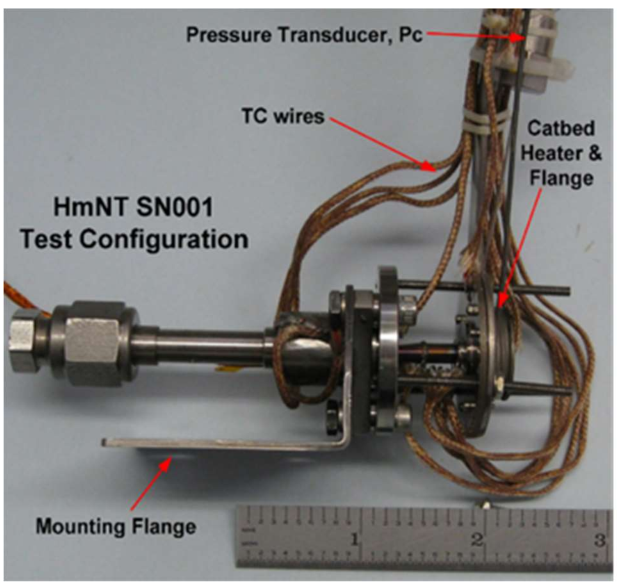
In order to reduce the minimum ibit of a thruster, it is necessary to reduce the amount of fuel delivered to the thruster in a short pulse. This could be accomplished by:

A. Developing a valve that opens faster and closes faster. This enables the valve to respond to a shorter electrical pulse width, thereby reducing the propellant flow time and the minimum ibit.

B. Developing a smaller thruster and making the flow paths between the valve and the thruster smaller, such that the amount of propellant that flows through these paths is reduced (for a given commanded pulse width).

The X2000 (technology development) Project provided funding to develop such a valve at Moog Inc., Space and Defense Group, under contract from Jet Propulsion Laboratory. This valve, designated the Moog P/N 51-271, has been fully qualified and is ready for flight. It has an opening time of less than 2 milliseconds, and a closing time of less than 1 millisecond. More details on the valve development can be found in Reference 2. The 51-271 valve was mated to an existing version of the 0.9 N Aerojet MR-103, making no changes to that thruster. An extensive Δ-qualification test program of the thruster/valve combination was performed.[3, 4] All the previous capabilities and qualification heritage of the MR-103 thruster were maintained, while providing a four-fold reduction in the minimum ibit by virtue of the new Moog 51-271 valve.

The next step was to develop a miniaturized hydrazine thruster to further reduce the impulse-bit, while also meeting our other design objectives. A proposal was submitted to the Mars Technology Program Office at the Jet Propulsion Laboratory, to advance the development of the HmNT. The new design miniaturized the nozzle and throat area, the catalyst bed (catbed), and the injector. The thruster-to-valve interface was designed to be compatible with the aforementioned 51-271 valve.[2] The thruster components were fabricated, assembled, and mated to this valve.



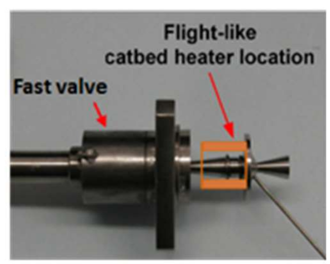


Figure 1. HmNT SN001 Test Configuration (left); a More Flight-Like Configuration (right).

Figure 1 shows a photo of HmNT prototype SN001, as tested, and a non-tested but more flight-like unit assembled for display. The test configuration has additional features such as instrumentation that are not necessary for a flight configuration. The accommodation of the test instrumentation compromised Isp performance but provided valuable data for design validation. A very useful parameter to be measured in test is the thrust chamber pressure (Pc). To prevent the pressure transducer from overheating, it is located ~2 inches away from the nozzle and connected by a microtube that is laser welded to the nozzle chamber immediately upstream of the throat. A large metal flange provides structural support for the delicate Pc microtube during all the assembly and test operations. A second large metal flange supports a commercially available and non-optimized catbed heater.

This location for the catbed heater is inefficient but allowed easy access to the catbed for multiple thermocouples to obtain a temperature profile from upstream to downstream along the catbed. These two large metal flanges surround the nozzle and produce large heat sinks that reduce performance because they cool the decomposition gases. As shown in the photo on the right in Figure 1, a flight version of the HmNT would not have these large heat sinks, and the catbed heater would be located more efficiently around the cylindrical part of the catbed itself, helping to insulate the catbed from heat loss. A thermal heatshield would also be installed around the catbed and nozzle. Pc is not usually measured on flight thrusters, so the pressure transducer would not be needed. Only two temperature sensors are typically flown: one on the valve and one on the catbed.

TESTBED INFRASTRUCTURE

The HmNT testbed performed very well against very challenging requirements. The HmNT infrastructure includes:

- A vacuum facility at the Jet Propulsion Laboratory, including a 4 ft × 8 ft vacuum chamber (Figure 2), modified for testing the HmNT in the relevant environment. The facility was able to maintain vacuum levels of ~0.5 Pascal or less (< 4 millitorr) during firings with its Roots blower and a Kenney KT850 vacuum pump.
- A compact hydrazine feed system that sits, self-contained, on the thrust stand inside the vacuum chamber.
- A thrust stand capable of measuring thrust in the low milliNewton range and ibits in the 10s to 100s of μN-s range. The thrust stand was designed by Dr. John Ziemer.
- A data instrumentation system capable of measuring the thrust stand response, the very fast response-times of the HmNT valve and providing command and data acquisition for the feed system, HmNT valve and thruster.

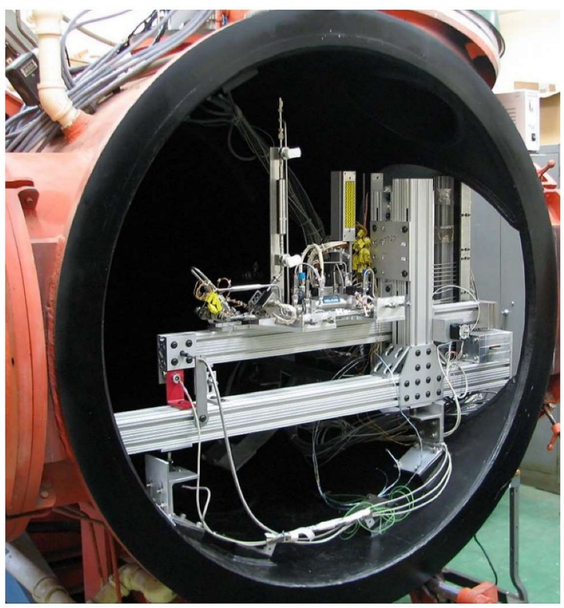


Figure 2. HmNT Thrust Stand in Vacuum Chamber

The measurement of thrust and impulse is accomplished using two independent methods—the thermodynamic approach, using Pc and temperature measurements, and the "spring" method as described in Dr. Ziemer's paper.[5] The data instrumentation system reports the latter method in near real-time, and collects the Pc and temperature data for separate analyses.

The thrust stand acts as a damped sinusoidal spring which, when thrusted against, will displace from its stationary position a distance proportional to the force (thrust) that caused the displacement. Accurate calibration of this displacement with respect to time yields the actual thrust (or impulse) produced by the thruster. Measurement of the displacement is affected by a very accurate Linear Variable Distance Transducer (or LVDT) which measures displacement from 1 to 1600 micrometers ± 3 micrometers. The LVDT is the primary measurement device used for thrust determination.

The range of thrust that can be measured is determined by two factors, the strength of the installed spring and the maximum displacement range of the LVDT, which for the HmNT test stand is ±1600 micrometers. The thrust stand pivot springs can be changed in order to affect different measurement ranges. A "less stiff" spring causes a longer thrust stand natural period, which is better suited to measure smaller impulse. For example, if measurement of low ibits are required (typically ~5–50 millisecond pulses for the HmNT), less "stiff" springs are used. For the measurement of longer pulses (> 50 milliseconds up to steady-state), stronger springs are used.

VACUUM HOT-FIRE TEST RESULTS

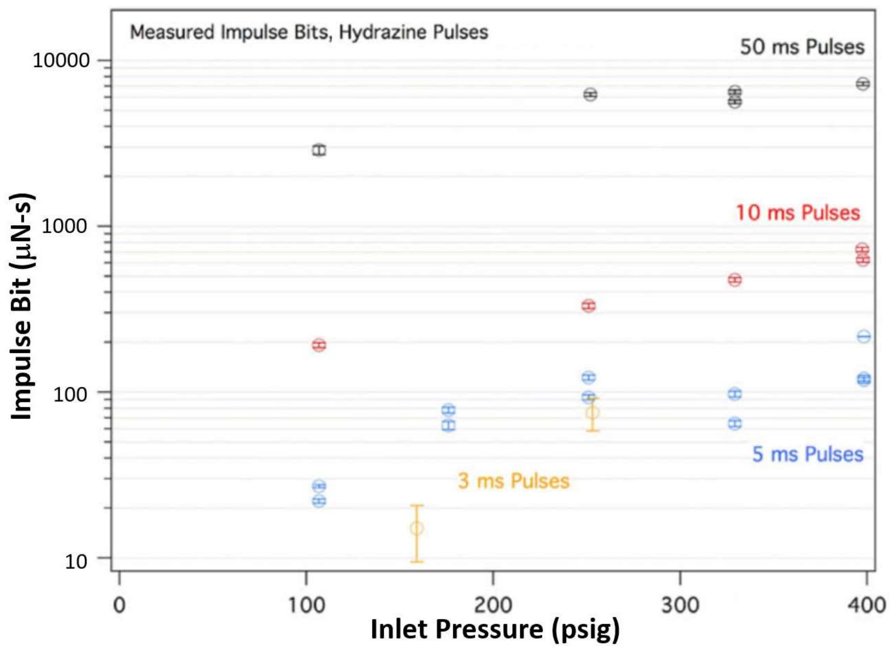


Figure 3. HmNT Minimum ibits Measured in Vacuum Hot-fire Tests at 5, 10 and 50 ms On-times.

Figure 3 shows ibits decreasing as pulse width decreases and, a decrease in ibits with decreasing inlet pressure for a given pulse width. The 5 ms commanded pulse width produced minimum ibits of 25–120 μN-s over the pressure range, with good repeatability. Uncertainty bars are shown around each set of data points. The HmNT is capable of producing minimum ibits even smaller than 25 μN-s, since the valve can produce pulses as short as 2 ms with excellent repeatability. However, the thrust stand (with the spring system that was installed at that time) could not measure, with much confidence, the impulse produced by pulse widths shorter than 5 ms. Notice the large uncertainty bars around the 3 ms pulses. Changes to the thrust stand spring system would enable measurement of ibits much smaller than those plotted in Figure 2. We can reasonably estimate that the HmNT can produce repeatable ibits less than half of those produced by the 5 ms pulses.

Table 1. Reduction in Minimum ibit and Steady-State Thrust for the HmNT vs. the MR-103H.

Comparison Parameter	Current SOA Aerojet MR-103H	HmNT	Reduction in Minimum ibit and Thrust
Min. ibit @ 2758 (400 psia)	8,787 µN-sec	120 µN-sec	73×
Min. ibit @ 689 kPa (100 psia)	2,900 µN-sec	25 µN-sec	116×
Thrust @ 2758 kPa (400 psia)	1.07 N	0.134 N	8.0×
Thrust @ 689 kPa (100 psia)	0.27 N	0.035 N	7.8

Table 1 shows how much the HmNT was able to reduce minimum ibit and steady-state thrust compared to the current SOA in minimum ibit, the Aerojet MR-103H. The MR-103H has the smallest minimum ibit of any hydrazine thruster flown to date. The HmNT produced minimum ibits at least 70 times smaller at 2758 kPa (400 psia), and more than 100 times smaller at 689 kPa (100 psia) than the MR-103H. Steady-state runs were conducted to establish the fundamental operating characteristics of the design, which is difficult, if not impossible to do in pulse mode alone.

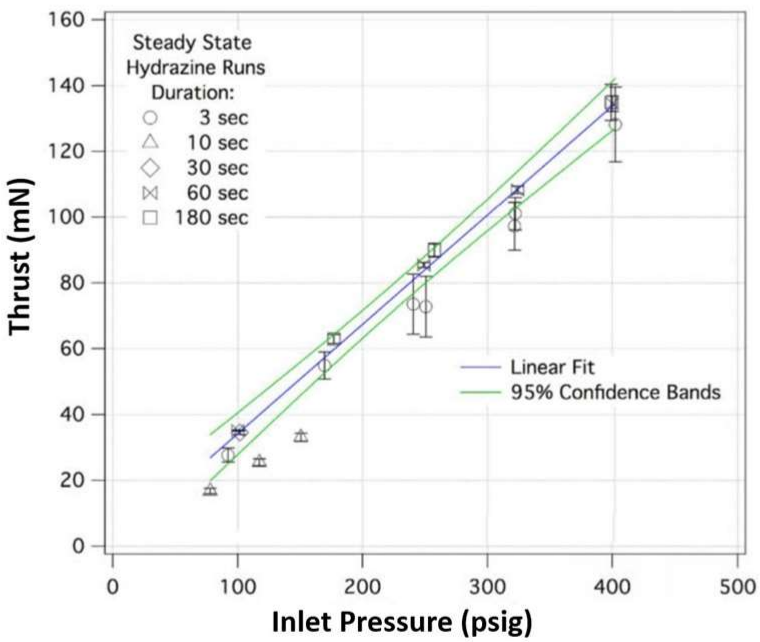


Figure 4. HmNT Hot-Fire: Steady-State Runs.

Figure 4 shows how steady-state thrust level varies with inlet pressure. Steady-state hot-fire tests were conducted at five points across the inlet pressure range to establish a linear fit that can be used to predict the thrust at any inlet pressure within that range. The lowest thrust level demonstrated was ~20 mN steady-state thrust at the lowest pressure tested, ~517 kPa (75 psia). The highest thrust level demonstrated was ~134 mN at 2758 kPa (400 psia). Three long-duration runs of 180 seconds were completed at 1207, 1724, and 2758 kPa (175, 250, and 400 psia). These 180 second runs demonstrate the HmNT's capability to handle the fast-rate to slow-rate transitions that a spacecraft will experience after using larger thrusters for telecom turns-to-Earth, Sun-pointing, or a re-targeting slew, then returning to the much slower rates required for precision pointing.

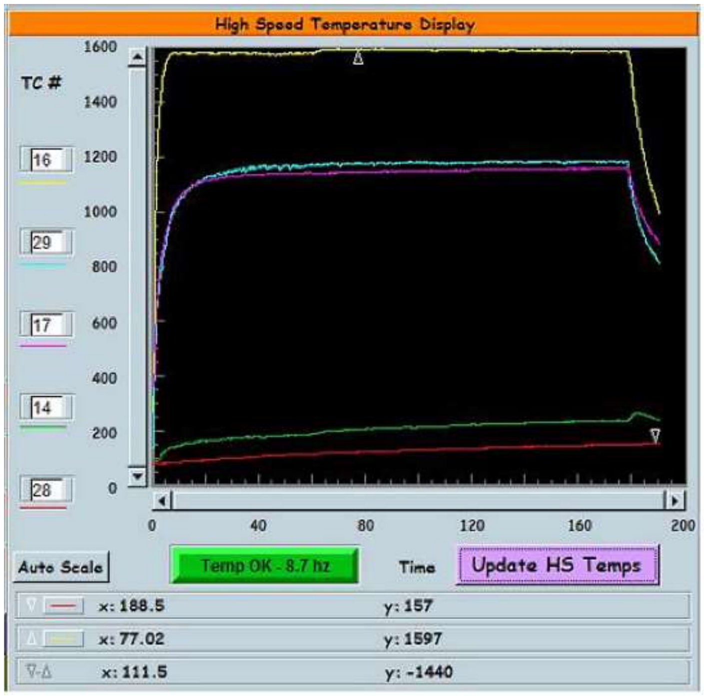


Figure 5. Thruster and Valve Temperatures During a 180 Second Steady-State Hot-Fire Test

The steady-state tests also characterized the thermal design of the HmNT. The temperature traces in Figure 5 show two main characteristics of interest. 1) The valve temperature, TC-28 (red trace) located on the valve flange, is well below the 350°F that the valve is qualified for. Even though these 1st generation prototypes of the HmNT were constructed of all stainless steel parts, which are not the optimum choice for a proper thermal design, these tests confirmed that the thermal design of the HmNT is robust. A flight design of the HmNT will employ high temperature metal alloys that are less thermally conductive and would do an even better job of mitigating the heat soakback. 2) The large heat sinks, primarily the two large metal flanges surrounding the nozzle, cooled the decomposition gases, as predicted, and reduced performance. At the injector end of the catbed TC-16 (yellow trace) reads 1597°F. At the nozzle end TC-17 (purple trace) reads 1160°F, and the plume temperature, TC-29 (blue trace) reads ~1190°F. Another possible contributor to the cooler downstream temperatures is that the catbed may be too long, causing excess ammonia dissociation, which is endothermic, and also hurts performance. A second generation HmNT design will test a shorter catbed to optimize the design. These temperature plots show the highest catbed temperatures recorded, during the longest burn at the highest inlet pressure tested, 2758 kPa (400 psia), producing 134 mN Thrust. An aggregate Isp was calculated by totaling the impulse for 37 steady-state runs between 3 seconds and 180 seconds, during which 49 grams of hydrazine were used. The result was an Isp of 151 seconds. The flight configuration with proper thermal design should achieve a steady-state thrust Isp of ~ 200.

MISSION APPLICATION—REPLACE OR BACKUP REACTION WHEELS

Precision pointing of spacecraft is typically performed using RWAs. As with all technologies, RWAs have their advantages and disadvantages. They are easy to model and have significant heritage. However, like any hardware, RWAs have limited life, and should not be expected to run smoothly forever. The vibration "jitter" associated with RWAs can be mitigated somewhat using sophisticated wheel balancing techniques. Even so, the jitter often worsens to the point of interfering with sensitive instruments. The precision pointing capability is degraded, or in some cases lost altogether. Recent failures of reaction wheels have cut short and/or limited the mission functions of several spacecraft including Dawn, Mars Odyssey, and Kepler among others. Some missions have used the spacecraft's thrusters to assist the ailing RWAs after problems developed, typically, using thrusters for the coarser, or higher rate turns, to prolong the useful life of the RWAs. However, the current SOA small thrusters cannot provide ibits small enough to provide a true functional backup for RWAs.

The mass of a RWA system can add up to a significant portion of a spacecraft's mass (including wheels, electronics, cabling, secondary structure for mounting). RWAs use significant amounts of energy and have high peak power demands, and a set of RWAs can cost double, or more, the cost a set of HmNT thrusters.

An early trade study[6] showed that thrusters alone could provide precision pointing, thereby backing up or replacing RWAs, if small enough ibits could be achieved. Precision pointing is achieved via single or double-sided deadband attitude control. Thruster pulses can cause a vibration that will ring for some period after each pulse. However, with small ibits, the magnitude and duration of the ringing is reduced, and if the duration between pulses is long enough, the spacecraft's instruments will enjoy quiescent periods between pulses. That study used analytical predicts of the HmNT performance before hot-fire tests were performed. It also used information from proposed Mars missions that were never flown, and by necessity made assumptions about pointing requirements and disturbance torques.

A new series of trades is being conducted using actual flight data from current and past missions, to compare the HmNT to RWAs. The HmNT was designed to produce ibits small enough to provide true functional backup for, or replacement of RWAs, and these new trade studies are using as-tested data from vacuum hot-fire tests of the HmNT. Early results indicate that replacing RWAs with a set of HmNTs can often save system mass, power, and cost. Quantifying these potential system benefits requires performing an in-depth study that considers pointing requirements and disturbance torques on the spacecraft. The mass, power, and cost of the RWAs vs. HmNTs, and system resources such as additional propellant, drive electronics, cabling, battery sizing, and secondary structure must also be considered. A set of 12 HmNTs can easily be added to the existing hydrazine propulsion system to provide precision pointing, for < 0.5 kg in propulsion hardware, plus the cabling, valve drivers, and secondary structure. One of the objectives of these new trade studies is to develop a set of criteria that mission designers can use to quickly assess which missions are good candidates for using the HmNT to replace reaction wheels. The results of these trade studies will be the topic of a follow-on paper.

MISSION APPLICATION—FORMATION FLYING AND DOCKING MANEUVERS

Precision delta-V applications are enabled by the range of thrust and impulse provided by the HmNT. The degree of precision is dependent on a number of variables including the mass of the spacecraft and the moment arm of the thrusters. In general, these capabilities can be applied to:

- proximity operations and docking maneuvers

- formation flying
- primary attitude control for SmallSats, and CubeSats
- primary delta-V for CubeSats.

Representative velocity control requirements for docking and proximity operations are on the order of 1 cm/s. As a rule of thumb, control resolution should be smaller than at least one tenth the requirement (1 mm/s) for linearity of response. For a 1 kg or more massive CubeSat/SmallSat, the HmNT minimum ibit easily meets this goal with a velocity control resolution on the order of 0.12 mm/s.

As the mass of a spacecraft increases, the velocity control resolution improves. The relative-orbit control performance of the 150-kg PRISMA formation flying mission was limited by its velocity control resolution of 0.7 mm/s.[7] The HmNT would provide several orders of magnitude improvement. Of course, the trade-off is maneuvering agility. However, if a large acceleration is needed, as noted, a single larger hydrazine thruster can be added to the spacecraft (PRISMA carried 1-N thrusters) with little impact to the system.

Similarly, the PROBA-3 mission[8]—demonstrating precision sub-mm formation control to synthesize a solar coronagraph at an altitude of 60,000 km to emulate the low-disturbance environment of deep space—will carry an array of 10-mN cold gas thrusters for precision formation flight. Additionally, the main SmallSat must carry four 1-N monopropellant engines for orbit transfer. The system complexity, performance, and reliability could be simultaneously improved by switching the cold gas thrusters to HmNTs. The entire cold gas propulsion system could be removed, and reliability would therefore be improved by eliminating the gas leakage. The specific impulse of the formation flight thrusters would increase from ~50 s to ~200 s. Assuming an inlet pressure of ~ 200 psia, the thrust level of the HmNT is ~70 mN, which is larger than the 10-mN thrusters baselined for PROBA-3. However, the fast valve of the HmNT makes the velocity resolution comparable. Reference 2, Fig.6 shows velocity control requirements on the order of 10 um/s to maintain the sub-mm relative control. At the same inlet pressure of ~ 200 psia, the HmNT can achieve a minimum ibit of 70 µN-s with a pulse width of slightly less than 5 ms. For the ~500 kg main spacecraft, the minimum ibit of 70 µN-s translates into velocity control of ~0.1 um/s, or 20x better than the requirement.

A CubeSat example is the CanX-4 and CanX-5 precision formation flight demonstration mission.[9] The propulsion system consisted of four ~30 mN cold-gas thrusters with an Isp of 45 s, producing 18 m/s of total delta-V. This thrust level is precisely the HmNT thrust range but, again, the HmNT comes with an Isp greater than 200 s. While an exact trade study would account for the increased piping and thruster mass of the HmNT, the delta-V could be increased by up to a factor of 5 to ~100 m/s. Admittedly, an important consideration in a university-led mission is avoiding the handling of hydrazine.

For delta-V and attitude control of CubeSats, a comparable system is the Vacco ChEMS Micro-Propulsion system (MiPS).[10] It consists of five 55-mN thrusters with an Isp of 65 s and a minimum ibit of 1000 uN-s and fits within the volume of 0.3-U. The point here, however, is the HmNT thrust level matches the Vacco MiPS while providing significantly better specific impulse and minimum ibit at the cost of increased volume.

A report on mission concepts for smallsats[11] identified missions such as RELIC (30+ 3U CubeSats to investigate radio emission from black holes) and ExCSITE (multiple, expendable CubeSat flybys of Europa from a carrier-ship) that require a precise propulsion system such as the HmNT. The farther up the gravity well from Earth, the more important high Isp is to reduce mission mass.

While electric propulsion is baselined for missions such as RELIC that are "near Earth," solar-powered electric propulsion is not feasible at Jupiter for ExCSITE. Further, the HmNT remains a viable candidate for missions such as RELIC. For ExCSITE, the HmNT is ideal: high Isp for large delta-V, small impulse bit for precise attitude control, and can function for a reasonable duration with the catbeds heated from a battery. As an example, the HmNT system could enable precision-pointing of a high-resolution, narrow field-of-view camera towards Europa's surface.

OVERALL SUMMARY AND CONCLUSIONS

The main objective of the HmNT design was to produce minimum ibits small enough to provide the precision pointing required to replace reaction wheels, and the capability for precision delta-V needed for rendezvous, docking, and formation flying maneuvers.

The HmNT provides mission and spacecraft designers options that can save mass, power, and cost. It fits seamlessly into existing hydrazine propulsion system designs that are used on the majority of spacecraft.

Work to compare the HmNT to RWAs using actual flight data from current and past missions is in progress. These trade studies will develop a set of criteria that mission designers can use to quickly assess which missions are good candidates for using the HmNT to replace reaction wheels. The results of these trade studies will be the topic of a follow-on paper.

Vacuum hot-fire tests have demonstrated that all the original objectives were met or exceeded. With over 350 hot-fire tests to date, the HmNT has demonstrated that it can operate at any inlet pressure between 689.6 kPa–2757.9 kPa (100 and 400 psia) and produce minimum ibits of 25–120 μN-s over that range of pressures. The HmNT can operate steady-state for at least 180 seconds. That capability is more than enough to handle the transition from relatively fast rotational rates from larger thruster activities, to the much slower rates required for precision pointing.

The testbed infrastructure is capable of measuring thrust in the milliNewton-to microNewton range, and ibits in the 10s to 100s of microNewton-seconds range for hydrazine thrusters, in the relevant vacuum environment. Future improvements to the thrust stand design will enable impulse bit measurements even smaller, potentially into the sub-μN-s range.

The HmNT uses a fully qualified fast-acting valve, the Moog P/N 51-27, mated to a newly designed miniature thruster. The thruster is currently at TRL 5. While a significant amount of work remains to bring this thruster technology to flight qualification status for a particular mission, the capabilities demonstrated thus far are very promising. More detailed information on the HmNT can be made available to support missions that wish to pursue this innovative technology.

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