Politecnico di Milano

`Second Assignment`

Space Systems Engineering and Operations

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Contents

1 Architecture

MESSENGER's propulsion system consists in a pressurized bipropellant, dual-mode system feeding a set of 17 thrusters, in order to fullfill mission's requests in terms of Δv changes. The bipropellant mode uses hydrazine (N_2H_4) as fuel and nitrogen tetroxide (N_2O_4) as oxidizer. On the other hand, monopropellant mode uses hydrazine. Down in Figure 1 is the subsystem's arrangement:

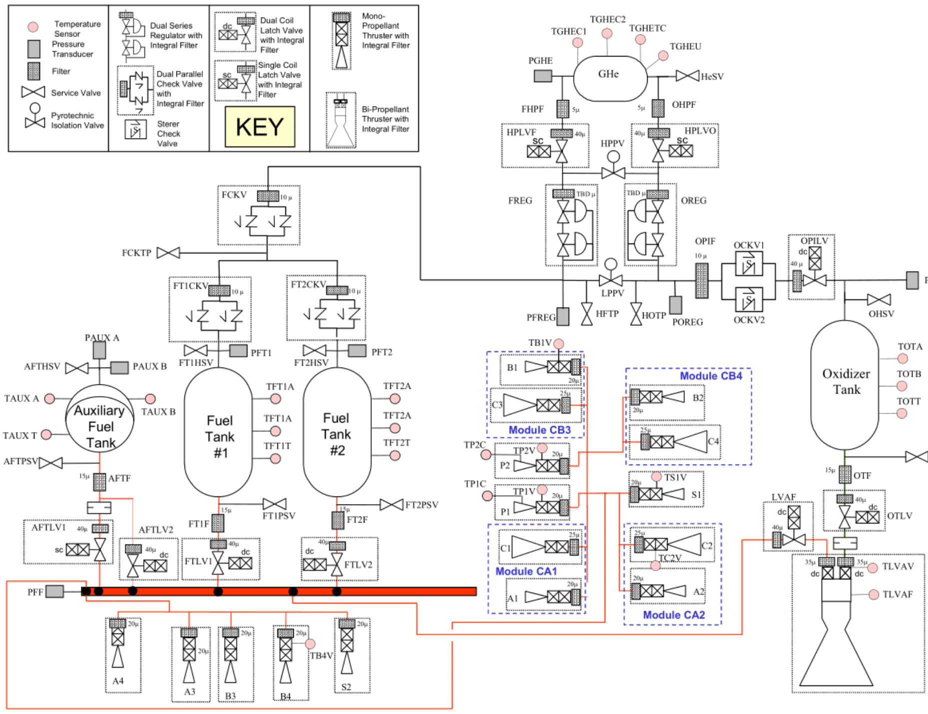

Figure 1: Schematics of the propulsion subsystem

1.1 Tanks

The two fuel tanks storing approximately 365.34 kg of fuel, and the oxidizer tank storing 231.61 kg of oxidizer, are positioned symmetrically with respect to the spacecraft's centerline in order to easily maintain mass control during the firings. Both the fuel and the oxidizer tanks are included in a pressure-fed system: they are pressurized with helium, which is contained in a high-pressure tank at approximately $232,7\ bar$.
The fuel tanks are kept at around 19.5 bar during the firing, while the operating pressure of the oxidizer tank is 19.1 bar. The fuel tanks are-pressurized before firing.
An auxiliary refillable fuel tank is mounted on the side of the spacecraft; however, this is not linked with the helium tank and operates in a blowdown mode, between 20.7 and 7,58 bar.
Choosing a pressure-fed solution for the main tanks and a blowdown for the auxiliary one has several advantages: despite the need to pressurize the tanks, this architecture allows the system to be lighter with respect to a pump-fed system, which is way more complex and requires more space to be implemented in the spacecraft, and would increase the total mass to suboptimal levels. Furthermore, this comes with acceptable properties in terms of performance, while the use of a purely blowdown system would lead to lower and lower engine efficiencies as the propellant load is used and its pressure decreased.

1.2 Propellant supply

Once the pressurization system is activated, in order to reach the tanks, the pressurized helium must pass through filters, series of redundant regulators, latch valves, check valves and cross strapping pyro valves, whose role is crucial since they provide the apparatus cross strapping capability in case of latch valves or regulators failure. Pipes and valves link the main and the auxiliary fuel tanks for operations of refilling/draining. The propellants flow from the pressurized tanks to the engines or to the auxiliary tank by following the pressure gradient.

1.3 Thrusters

The set of 17 thrusters includes three different thruster types, with respect to the force they shall provide to the spacecraft. Figure 2 shows the spatial configuration of the thrusters.
The **LVA** (Large Velocity Adjuster) thruster is the bipropellant portion of the system and provides a thrust

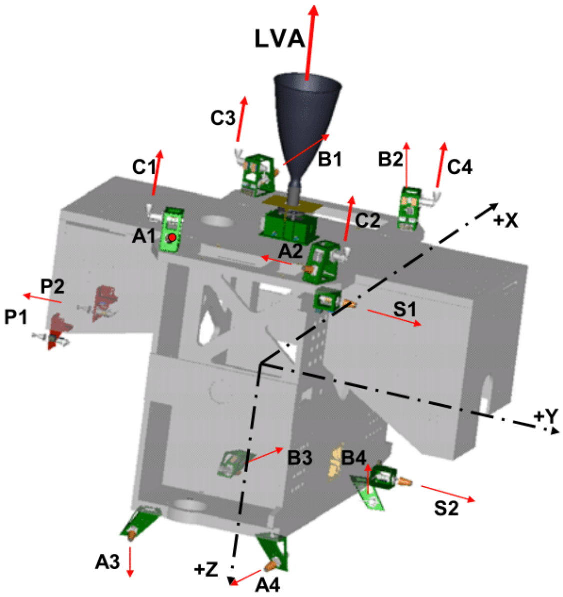

Figure 2: Arrangement of thrusters

level of 667 N and a specific impulse of 316 s, in the -Z direction; it is the most powerful engine of the spacecraft, grating major Δv changes. Four monopropellant thrusters disposed in the -Z side (identified as **C**-thrusters) provide a force of 22 N and a specific impulse of 230 s each. Finally, twelve monopropellant engines grant a force of 4.4 N and a specific impulse of 220 s each. More specifically, eight thrusters (**A** in the +X side and **B** in the -X side) are disposed in double canted sets of four for redundant attitude control on the three axis, in modules together with the C-thrusters, even though they yield force in different directions. The remaining four motors (**S** in the +Y side and **P** in the -Y side) are meant to provide velocity changes in the sunward direction (S-thrusters) or in the away-from-the-sun direction (P-thrusters).
The spatial configuration of the A, B, S, and P motors ensures that no maneuver requires a null command, limiting the waste of propellant. Furthermore, it is possible to split the required thrust between opposing thrusters on opposite sides of the spacecraft in order to cancel out any residual force. That allows to have a finer attitude control and to use the minimum number of burns to complete a specific task.

2 Primary and Secondary Propulsion

The propulsion system's duty is to provide MESSENGER with the ΔV requested throughout its operational lifetime in order to fulfill its mission. Two types of propulsion are identified:

- **Primary propulsion**: orbital changes and correction;
- **Secondary propulsion**: station-keeping and attitude control.

Table 1 illustrates the different functions of the different engines.

Thruster	Charge	Tasks
LVA	Primary propulsion	Operations requiring the highest ΔV budget
C	Primary propulsion	Thrust vector steering forces during LVA burns; provide propulsion for smaller ΔV maneuvers
A, B, S, P	Secondary propulsion	Fine attitude control burns; small ΔV burns; momentum management

Table 1: *Thrusters' tasks*

3 Justification of the selected propulsion type

Before explaining the functioning of each mode, the first maneuver required by the spacecraft after being deployed is the **Detumbling**. All eight A and B attitude control system thrusters are fired to stabilize the spacecraft. The maneuver lasted for a total of 160 seconds where the goal was to spend the least possible amount of ΔV. After completion of thruster firings and system safing, cruise phase propulsion system heaters were enabled and therefore the spacecraft switched to Cruise Phase Mode.

3.1 Operations / Phases

The Propulsion System has four operational modes: a cruise phase mode and three thruster operational modes.

The **Cruise Phase Mode**, is the only phase that does not require the use of thrusters to perform a maneuver. In this mode, the propulsion subsystem temperature is maintained within its operational range using heaters.

The **Mode 1** is characterized by the use of the auxiliary fuel tank for the whole maneuver. In this mode, either the 22N or the 4.4N monopropellant thrusters are operated in blowdown configuration to provide small-ΔV trajectory correction maneuvers or momentum dumps.
Mode-1 maneuvers execute in two segments: main burn and tweak. The main burn segment is used to achieve the ΔV target, and the tweak segment follows to maintain spacecraft attitude. Momentum dumps are executed only as a tweak segment because they are not meant to impart any net ΔV. These fine adjustments justify the need of the 4.4N monopropellant thrusters. At the end of the tweak, the propellant system's work is over and the attitude control is taken over by the reaction wheels. As a matter of fact, using these thrusters is also justified in order to desaturate the reaction wheels if needed.

The **Mode 2** is characterized by the use of both the 4.4N and 22N monopropellant thrusters pressure-fed from the main fuel tanks as the primary propellant source.
Mode-2 maneuvers execute in three segments: settle burn, main burn, and tweak. Given that the main propellant tanks do not have propellant-management devices, a monopropellant thruster settling burn must be executed from the auxiliary tank to move the propellant to the main tank outlet before it can be accessed. To provide the necessary direction settling force, the A1, A2, B1, and B2 top deck 4.4N thrusters are nominally fired for 15 seconds. For the main burn, the high-pressure fuel latch valve is opened, and the 22N thrusters or 4.4N thrusters oriented in the –z direction are operated using one of the pressurized main fuel tanks. As with a Mode 1 maneuver, the main burn segment ends when the ΔV target is achieved, and the tweak segment is used to keep the spacecraft attitude. Since both auxiliary fuel tank latch valves remain open for the entirety of the maneuver, the auxiliary tank is refilled while the main burn proceeds. Throughout the maneuver, attitude control is accomplished by off-pulsing the primary thrusters and on-pulsing 4.4N thrusters.

The **Mode 3** is used for large ΔV maneuvers and uses the bipropellant LVA thruster, which is pressure-fed from the main fuel and oxidizer tanks. This N_2H_4/N_2O_4 - based thruster is vital in order to provide the spacecraft with the required Deep Space Maneuvers already planned during the numerous interplanetary legs but also to perform the Mercury Orbit Insertion which requires a huge amount of ΔV.
Mode 3 maneuvers execute in five segments: settle burn, refill burn, main burn, trim burn and tweak. The settle and tweak segments are the same as those of a Mode-2 maneuver. The settle burn is followed by a separate refill segment. During this segment, the top deck 4.4N thrusters are fed by a main fuel tank and fire for a predetermined duration to refill the auxiliary tank. For the main burn, all three latch valves upstream of the main propellant tanks are opened, and the LVA is operated using the pressurized main fuel and oxidizer tanks as the primary propellant sources. The four 22N thrusters are on-pulsed for LVA thrust vector control, and the 4.4N thrusters are on-pulsed for fine attitude control. After the LVA has achieved a certain percentage of the required ΔV, the system transitions to the trim segment. During trim, the 22N thrusters are used to ensure a more precise completion of the required ΔV. To maintain a manageable spacecraft center of mass, the main fuel tanks are switched every 20 seconds during the main and trim burn segments by opening and closing their outlet latch valves. Otherwise, the thrust vector will generate a net torque that the 22N thrusters are not able to control.

3.2 DeltaV budget breakdown

The ΔV budget is split into different type of maneuvers, namely :

- Detumbling (DET)
- Deep Space Maneuvers (DSM)
- Trajectory Correction Maneuvers (TCM)
- Mercury Orbit Injection (MOI)
- Orbit Correction Maneuvers (OCM)
- Momentum Dumps (MD)

The very first maneuver to be implemented was the detumbling in order to stabilize the spacecraft.

	ΔV [m/s]	Date	Mode	Thrusters Used
DET	0.46	3 Aug 2004	1	A,B

Table 2: *Detumbling*

To begin with, the DSM are Trajectory Control Maneuvers (TCM) with the largest velocity change. They were done within the different interplanetary legs of the flight of MESSENGER all using Mode 3.

	ΔV [m/s]	Date	Mode	Thrusters Used
DSM1	315.6	12 Dec 2005	3	LVA
DSM2	227.4	17 Oct 2007	3	LVA,B
DSM3	72.2	19 Mar 2008	3	LVA
DSM4	246.8	4 Dec 2008	3	LVA
DSM5	177.8	24 Nov 2009	3	LVA

Table 3: *Deep Space Maneuvers*

Contingency maneuvers TCM-4, TCM-7, TCM-8, TCM-14, and TCM-17 were never implemented due to the achievement of sufficient accuracy with the prior TCMs. After TCM-19, only the aforementioned DSM3, DSM4 and DSM5 were required before the MOI. Future trajectory corrections were made using solar sailing techniques by orienting the sunshade and solar panels in an appropriate way.

	ΔV [m/s]	Date	Mode	Thrusters Used
TCM1	17.9	24 Aug 2004	2	C
TCM2	4.6	24 Sep 2004	2	C
TCM3	3.2	18 Nov 2004	2	C
TCM5	1.1	23 Jun 2005	1	S
TCM6	0.2	21 Jul 2005	1	P
TCM10	1.3	22 Feb 2006	1	B
TCM11	2.3	12 Sep 2006	2	C,S
TCM12	0.5	5 Oct 2006	1	B
TCM13	35.7	2 Dec 2006	3	LVA,P
TCM15	0.6	25 Apr 2007	1	B
TCM16	0.2	25 May 2007	1	B
TCM19	1.1	19 Dec 2007	1	B

Table 4: *Trajectory Correction Maneuvers*

About 31% of the spacecraft's propellant was required for Mercury orbit insertion (MOI) in order to place the spacecraft into its primary science orbit around Mercury. MESSENGER's thrusters slowed the spacecraft by 861.7 meters per second. As the spacecraft approached Mercury, the largest thruster was pointed close to the forward velocity direction of the spacecraft. The maneuver lasted about 15 minutes.

	ΔV [m/s]	Date	Mode	Thrusters Used
MOI	861.7	18 Mar 2011	3	LVA

Table 5: *Mercury Orbit Injection*

Already in Mercury's science orbit, the spacecraft needed to counteract the effects of the solar gravity which was acting on the spacecraft's orbit. Therefore, 4 Orbit Correction Maneuvers (OCM1, OCM3, OCM5, OCM6) were implemented at the apogee of the orbit to place MESSENGER with a minimum perigee distance of 200 km. The second and fourth maneuvers after MOI increased the orbit period to about 12 hours by speeding up the spacecraft near its closest distance from Mercury.

During the first extended mission of MESSENGER which started on 18 March 2012, two orbit-correction maneuvers lowered the spacecraft's orbit period from 11.6 hours to 8 hours finally depleting the oxidizer reserves by using the LVA thruster (OCM7). During the second extended mission of MESSENGER which began on 18 March 2013, four OCMs targeted a minimum altitude of 25km and 15km for the last OCM. During the last extended mission of MESSENGER which lasted 6 weeks until the crash, 7 OCMs targeted a specific minimum altitude. OCMs 13, 14, and 15 consumed nearly all remaining usable hydrazine from the auxiliary fuel tank. The final two OC maneuvers raised the spacecraft's minimum altitude above Mercury just enough to ensure impact onto Mercury during an orbit for which coverage by one of DSN's large antennas had been scheduled. Such a downlink arrangement enabled the transmission to Earth of nearly all images and science data remaining on the spacecraft recorder.

The final impact occurred the 30 April 2015.

	ΔV [m/s]	**Date**		ΔV [m/s]	**Date**
OCM1	27.8	15 Jun 2011	**OCM11**	19.3	24 Oct 2014
OCM2	4.0	26 Jul 2011	**OCM12**	9.6	21 Jan 2015
OCM3	24.9	7 Sep 2011	**OCM13**	3.1	18 Mar 2015
OCM4	4.1	24 Oct 2011	**OCM14**	3.1	2 Apr 2015
OCM5	22.2	5 Dec 2011	**OCM15**	1.8	6 Apr 2015
OCM6	19.2	3 Mar 2012	**OCM15A**	1.8	8 Apr 2015
OCM7	53.3	16 Apr 2012	**OCM16**	1.0	14 Apr 2015
OCM8	31.4	20 Apr 2012	**OCM17**	1.5	24 Apr 2015
OCM9	5.0	17 Jun 2014	**OCM18**	0.4	28 Apr 2015
OCM10	8.6	12 Sep 2014			

Table 6: *Orbit Correction Maneuvers*

Furthermore, there were a total of 181 Momentum Dumps, which include 1 Autonomous Momentum Dump (AMD) and 180 Commanded Momentum Dumps (CMD). Since they are Attitude Control Maneuvers, the ΔV they provide is negligible, very close to 0.00 m/s. They are all operated through Mode 1 thanks to the 4.4N attitude control system thrusters A and B.

The total ΔV budget adding everything together is of 2213.17 m/s.

4 Reverse Sizing

4.1 Propellant selection and masses

The propellant couple (hydrazine and nitrogen tetroxide) was selected thanks to its ability to guarantee high thrust when used as bipropellant, but also low thrust (needed for small maneuvers and fine adjustments) when used hydrazine as monopropellant. This solution allows the primary and secondary propulsion to use the same propellant, reducing the complexity and total mass of the system. Vacuum specific impulse in both bipropellant and monopropellant mode satisfies the requirements. Hydrazine and nitrogen tetroxide are also hypergolic, which grants reliable and repeatable ignition, high density and storable, all fundamental aspects when considering a long space mission. Furthermore this propellant couple has been tested and successfully used for many previous missions.

The total mass of the propellant needed for the mission has been calculated starting from the data shown in Table (7).

$I_{sp,bi}$ [s]	$I_{sp,mono}$ [s]	Δv [m/s]	m_s [kg]	O/F
316	230	2300	507.9	0.85

Table 7: Initial data

Knowing that $\approx 90\%$ of the Δv has been assigned to the primary propulsion, a weighted average specific impulse can be obtained. It can be then used in the rocket equation to calculate to total propellant mass:

$$m_p = m_s \cdot \left(exp\left(\frac{\Delta v}{g_0 I_{sp,avg}}\right) - 1\right) \cdot 1.02 \tag{1}$$

A margin of 2% has to be added to account for propellant residuals The masses of fuel and oxidizer are found, considering that ≈ 90% of the mass has been assigned to the bi-propellant motor.

$$m_{f,mono} = 0.1 \cdot m_p \qquad m_{f,bi} = \frac{0.9 \cdot m_p}{1 + O/F} \qquad m_{ox} = 0.9 \cdot m_p - m_{f,bi} \tag{2}$$

Results compared to the real messenger data are shown in Table (8)

–	m_p [kg]	m_f [kg]	m_{ox} [kg]
Reverse sizing	593.84	348.63	245.20
Real	596.95	365.34	231.61

Table 8: Propellant mass sizing results

The slight discrepancy may be explained by the need for a higher safety factor on the propellant mass of the monopropellant thrusters, such as the 100% safety factor on the predicted station keeping propellant needed.

4.2 Tanks sizing

In order to decide the number of tanks needed by the mission, the volume of propellant has to be analyzed. In this case the total volume of fuel required is more than double the volume of oxidizer. The best solution is then to use three main identical tanks (to minimize tank qualification, tooling and manufacturing costs), two for hydrazine and one for nitrogen tetroxide, and one smaller auxiliary tank filled with hydrazine. The use of an auxiliary tank is very effective for minimizing the mass and complexity of the three bigger tanks, since it allows to use in-line trap propellant management devices and vortex baffles in place of diaphragms. Small, 2 m/s, monopropellant settling burns use the auxiliary fuel tank, which has an elastomeric diaphragm, in blowdown mode prior to each bipropellant burn to settle the propellant at the tank outlets.

Propellant tanks need to be able to withstand the high pressures required, while minimizing their weight. For this purpose the best shape would be that of a sphere, which works perfectly for small sized tanks, like the auxiliary tank. For bigger tanks though, this option is very space inefficient, therefore the best choice becomes a cylindrical shape with two half domes at the end, used for the three main tanks and for the pressurizer tank. Material selection is of paramount importance in order to minimize the mass and to avoid tank corrosion and propellant decomposition. The lightest option for the pressurant tank is a titanium-lined composite over-wrapped leak-before-burst pressure vessel (COPV), an already flight-proven technology for helium tanks. Its use would not be safe for the propellant tanks, due to a lack of testing for pressure-fed systems. Instead, 6Al-4V titanium has been used, given its proven reliability and compatibility with both fuel and oxidizer, as well as its low density and high tensile strength.

In order to find the dimensions of the main tanks, 25% of unusable volume has been added to the volume of propellant. Then the value of the tanks radius has to be chosen, considering the trade-off between space efficiency and mass. For the purpose of this paper, the radius has been assumed to be 559 mm, equal to the real tank radius. The length, thickness of the cylindrical part and thickness of the hemispherical part of the tank can then be calculated as:

$$length = \frac{V - \frac{4}{3}\pi r^3}{\pi r^2} + 2r \qquad th_{cyl} = \frac{2P \cdot r}{\sigma} \qquad th_{sph} = \frac{P \cdot r}{\sigma} \tag{3}$$

Where r is the internal radius of the tank, P is the pressure inside the tank and σ is the yield stress of the material. A safety factor of 2 has been considered in the calculation of the thickness.
The mass is now found, and the results are shown in Table (9).

–	$length$ [mm]	th_{cyl} [mm]	th_{sph} [mm]	m_{tank} [kg]
Reverse sizing	998	1.2	0.6	6.6
Real	1041	1	0.5	9.1

Table 9: Tank sizing results

The difference in mass can be explained by noting that, while sizing the tank, vortex suppressors, baffles and inlet/outlet ports haven't been considered.

4.3 Pressurant selection and masses

The selected pressurant is Helium, very lightweight and inert, thus non-reactive. It also has been widely used for this purpose, proving its reliability.
Given the long operating time, an isothermal expansion (at $293K$) of the pressurising helium is modeled. Densities of the propellants are retrieved from literature and are $\rho_{Fu} = 1004.5\ \frac{kg}{m^3}$ and $\rho_{Ox} = 1450\ \frac{kg}{m^3}$. Density of helium is computed considering it a perfect gas through the state equation.
Helium initial storage pressure is known (i.e. $232,7\ bar$), and the propellants tanks are modeled as being pressurized at the pressure level required before engine ignition (i.e. $P_{tank} = 19.3\ bar$).
An extra 20% of pressurant is taken to account for a safety margin.

$$V_{He} = \frac{(V_{Ox} + V_{Fu}) \cdot P_{tank}}{P_{He,initial}} \cdot 1.2 \qquad (4)$$

$$m_{He} = V_{He} \cdot \rho_{He} \qquad (5)$$

	$m_{He}[kg]$	$V_{He}[m^3]$
Reverse sizing	2.459	0.0642
Real	2.295	0.0672

Table 10: Pressurization subsystem sizing

4.4 Feeding subsystem sizing

In order to retrieve the pressure in the tanks, nominal chamber pressures of 16 bar and 10.9 bar have been considered respectively for the main motor and for the 22N secondary motor (the highest nominal pressure one). Then using typical values of 10 $\frac{m}{s}$ for the flow velocities and 0.2 P_c for the pressure drop in the injector, the following results can be obtained (Table 11).

–	Oxidizer tank pressure [bar]	Fuel tank pressure [bar]	Auxiliary tank pressure [bar]
Reverse sizing	19.8	19.6	13.5
Real	19.5	19.1	20.7-7.58

Table 11: Feed system sizing

The auxiliary tank seems to be unable to satisfy the motor pressure requirements in some scenarios, but it has to be noted that, in order for the pressure to fall to the lower range limit, the tank has to be completely empty. Moreover the required pressure has been calculated using the motor's nominal pressure only, while in reality it is able to function with much lower pressures.

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