Human services mission to GEO satellites - Red Team - Spacecraft Design

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I. Introduction

THIS report aims at presenting the work of the spacecraft design group of the Red Team in the Human Spaceflight project about human services in geostationary orbit (GEO). While working on the project, many designs were produced or envisioned but after a few weeks of iterations mainly with the Logistics group, a final solution was chosen.

This solution is to be presented here, firstly by introducing all the vehicles and modules designed, precising their roles and their travel to the desired orbits after launch. Then, a focus is made on each module's characteristics and layout, providing detailed values about dimensions, mass, amount of propellant required and on/off-board systems.

II. Modules & mission overview

The purpose of the mission is to perform services in geostationary orbit. Thus, the spacecraft design team had to find ways to bring astronauts there and give them the means of realising those services. The final design is sketched in figure 1.

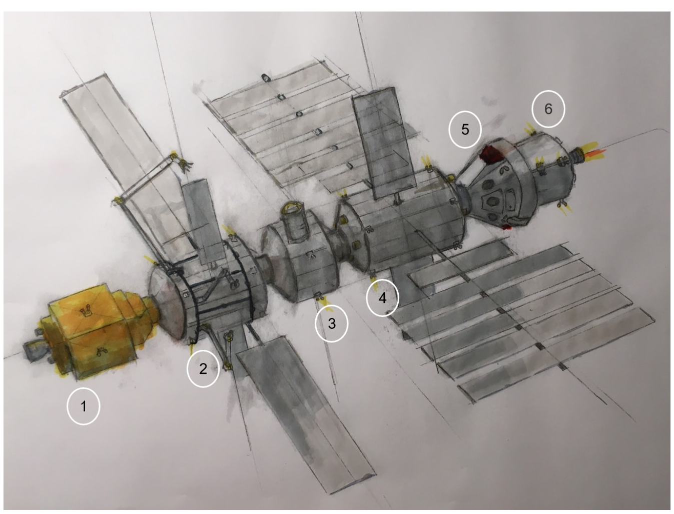

Fig. 1. Complete design overview

The modules and a brief explanation of their respective functions are the following:

1) MSM: Mission Service Module, used as a propulsion system unit.
2) MM: Mission Module, main living and working quarters for the duration of the mission.
3) AL: Airlock, to perform extravehicular activities (EVAs).
4) SM: Storage Module, used as a storage, power and Life Support System (LSS) generator unit.
5) LEV: Launch and re-Entry vehicle, transports the crew during launch and entry back to Earth.
6) LSM: LEV Service Module, propulsion unit of the LEV.

Nevertheless, the modules are not often in this position, all docked together. It actually only happens when the crew arrives in the chasing orbit, located just under GEO. There are actually 3 main configurations, depicted by figures 2, 3 and 4.

The first configuration is called the launch configuration because all visible modules are launched to LEO and travel together from LEO to the chasing orbit using electric propulsion (detailed on the Storage Module part). As there are no humans in the modules at this stage, time of travel is not a priority and electric propulsion allows to gain mass in terms of propellant and machinery.

The second configuration is the mission one. After the arrival and docking of the astronauts with the LEV and LSM (directly launched to the chasing orbit), all modules are docked like in figure 1. The astronauts then proceed to transfer to the mission module, after a couple days of preparation, packing and verification during which all the modules remain docked. Then, the MSM, MM and AL go to GEO to actually perform the mission there, for a duration of about three weeks.

The final configuration is the parking one. Once the astronauts are on their way towards GEO, the SM, LEV and LSM go to the parking orbit, at 25,000 km of altitude, using electric propulsion, to wait for the return of the astronauts. Once the mission is over, the Mission vehicles (MSM, MM and AL) join their counterparts in the parking orbit, using the chemical propulsion system of the MSM. Finally, astronauts transfer to the LEV and go back to Earth using the chemical propulsion system of the LSM, which is discarded before entering the atmosphere.

III. Launch and re-Entry vehicle

The Launch and re-Entry Vehicle (LEV) is a capsule inspired by the SpaceX Crew Dragon capsule [1], the NASA Orion Spacecraft [2] and the Apollo Capsule. Compared to the Crew Dragon it is down-scaled to be optimized for a crew of three astronauts. The overall layout is sketched on figures 5 6 and the design parameters are gathered in table I.

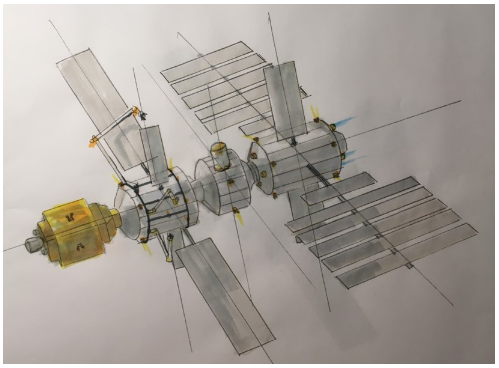

Fig. 2. Launch configuration

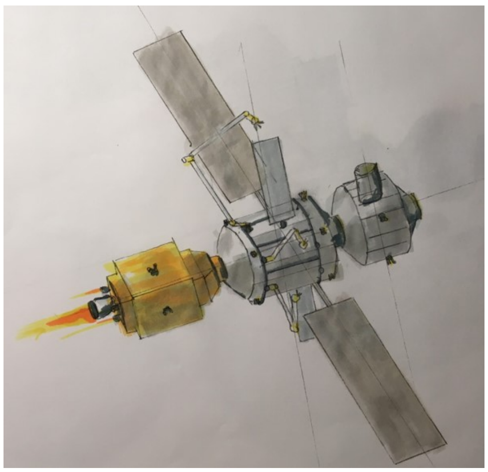

Fig. 3. Mission configuration

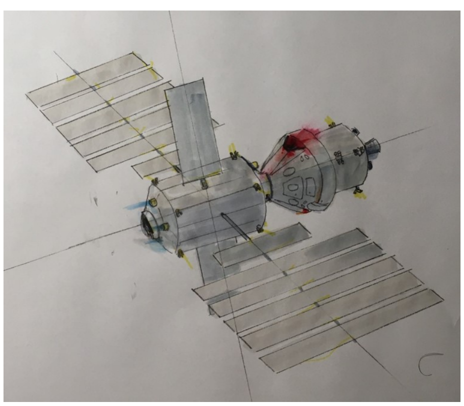

Fig. 4. Parking configuration

The capsule is equipped with four pairs of boosters similar to the SpaceX SuperDraco engines [3] capable of precision landing with propulsive decent. Thus, the spacecraft does not need parachutes for decent which means that the spacecraft can land at a spaceport instead of in the ocean. This will improve the lead-time and decrease the cost for re-use of the vehicle. The SuperDraco engines also serve as the launch abort system in case of a catastrophic failure during launch, see figure 8, which is an off-nominal case. (The Logistics group off-nominal case is also related to our work, we designed our

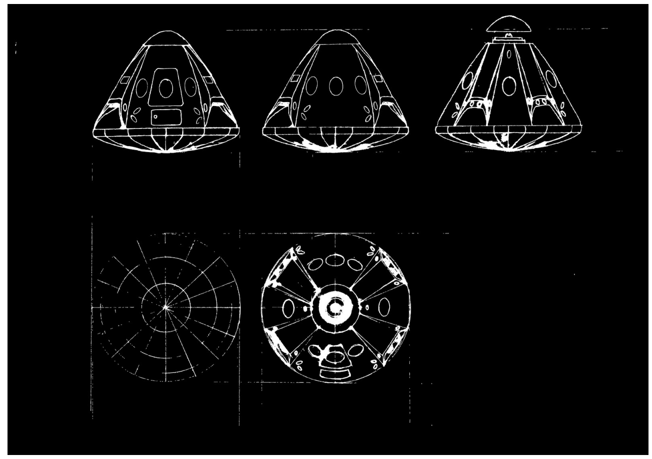

Fig. 5. Conceptual sketch of the Launch and re-Entry Vehicle (LEV)

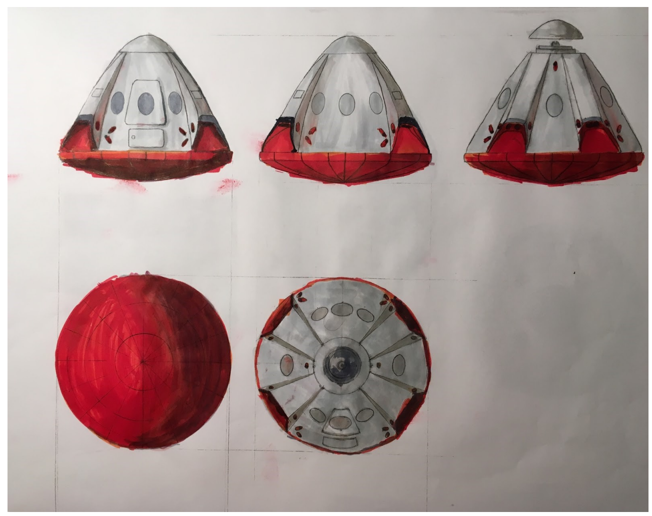

Fig. 6. Colored sketch of the Launch and re-Entry Vehicle (LEV)

vehicles so that they could achieve the manoeuvres required by this emergency). The weight of the 8 boosters and its fuel is roughly the same as the weight of a parachute system. The engines use hypergolic fuel. This means that it needs no igniter system since the fuel and the oxidizer self-ignites upon contact. The system is pressure fed and the fuel can be stored at normal temperature. The hypergolic combination

TABLE I
GENERAL SPECIFICATIONS OF THE LEV

Parameter	Value
Height	8 m
Diameter	3.7 m
Pressurized volume	10 m^3
Depressurised volume	14 m^3
Dry mass	6000 kg

TABLE II
GENERAL SPECIFICATIONS OF THE SUPERDRACO ENGINES

Characteristic	Value
Amount	8
Type	SuperDraco by SpaceX
Thrust	71 000 N
Fuel	MMH
Oxidizer	NTO

used is monomethylhydrazine (MMH) as fuel and Nitrogen tetroxide (NTO) as oxidizer. This combination was also used by the Apollo command module and is today used by SpaceX Dracoengines, visible on figure 7, with the specifications in table II.

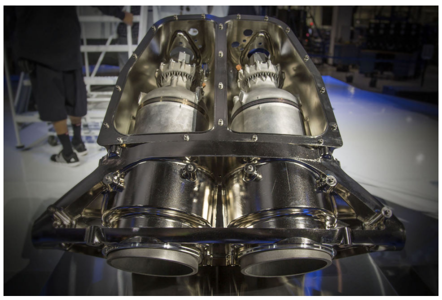

Fig. 7. SuperDraco engines. [3]

Fig. 8. Launch abort test for the Crew Dragon Capsule with the 4 pairs of SuperDraco engines. [3]

The capsule also has 16 RCSs (reaction control system) [4] for attitude and translation control primarily during re-entry, station keeping in orbit and docking. The RCSs are located at 16 spots on the vehicle to provide thrust capabilities in all possible directions. The RCS used is the famous R-4D engines originally developed for the Apollo program and is now developed and modified by Aerojet Rocketdyne. The engines are capable of 490 N of thrust and use a hypergolic fuel. The hypergolic combination used is the same as the main engines above: monomethylhydrazine (MMH) and Nitrogen tetroxide (NTO). The specifications are in table III.

On top of the LEV is a docking mechanism under a cap that is jettisoned in LEO. The capsule is equipped with a life support system for the duration of one week for a crew of three astronauts. The capsule also has the capacity to carry mission critical cargo such as repair equipment to the satellites it will service. Other major systems include radio-telecommunication to ground station and in space, manual and automatic docking system, manual and automatic navigation system by using the propulsion of the service module. Once undocked with the service module the capsule also has capabilities to perform a re-entry maneuver to decent through the Earth atmosphere at the right angle and then use the main engines for propulsive precision landing at an appropriate spaceport.

TABLE III
SPECIFICATIONS OF THE RCS THRUSTERS

Characteristic	Value
Amount	16
Type	R-4D Aerojet Rocketdyne
Thrust	490 N
Fuel	MMH
Oxidizer	NTO

The heat shield of the capsule is designed to withstand heat from the re-entry velocities built up during the decent trajectory from the rendez-vous orbit of 25 000 km. Thus the vehicle will experience higher velocities and heat than the Dragon capsule that is designed to return from LEO. The design of the heat shield is similar to the heat shield of the Apollo capsule. It is designed to withstand temperatures of 2800 degrees Celsius. The main structure is made of titanium and attached is a fiberglass made honey comb cell structure. The honeycomb cells are filled with an ablative heat shield material called avcoat [5], created by Avco / Textron. It is an exoxy novolac resin with special additives.

The purpose of the ablative heat shield material [6] is to lift the hot shock-layer gas away from the shields outer wall. This is achieved by burning and evaporating the ablative material which creates gaseous reaction products. These reaction products form a cooling boundary layer that protects the shield from heat flux. This process to drastically reduce the heat flux of the heat shields outer wall by a boundary layer is called blockage. The ablative process occurs at two levels; the outer part of the material melts and sublimes and the bulk of the material undergoes pyrolysis and expels gaseous products. The ablative process creates a char-layer that is composed of almost equal amounts of carbon and silica that is very heat resistant. The effect of the ablation can be seen on figure 9.

IV. STORAGE MODULE

The idea to have a module for the main power supply was inspired by NASAs Deep Space Gateway Concept [7]. We adopted the idea of using Solar Electric Propulsion which means that we use electric propulsion with Xenon as fuel and the solar arrays deliver the electrical power needed. We also have two docking ports at each end of the module. Figure 4 shows the SM docked to the Launch and re-Entry

Fig. 9. Avcoat material pre- and post-ablation [5]

Vehicle (LEV). The SM will be launched together with the Airlock (AL) and dock with the Mission Module (MM) and the Mission Service Module (MSM) in LEO. The main tasks of the module are listed below.

A. *Role of the module*

The Storage Module has to perform the following tasks:

- Uses electric propulsion to go from LEO to chasing orbit at 33000 km
- Uses electric propulsion to go from chasing orbit to parking orbit
- Provides power for recycling life support systems (water recycling and the main electric propulsion)

The technical aspects of the electric propulsion will be explained in IV-C . In total there are four main thrusters on the SM, two at each end of the module. That is because in the first configuration when it is docked to the AL, MM and the MSM (see Figure 2) it uses the thruster on the right end of the module and when it is docked to the LEV and goes from chasing orbit to parking orbit it uses the thruster on the left end. We decided to place thrusters on both sides because we considered that an autonomous docking maneuver which would be necessary with thrusters on only one side would be more dangerous and costly than placing additional thrusters.

Furthermore the SM has 16 maneuvering and attitude control thrusters which are placed all over the module (as can be seen in Figure 4) to guarantee movement control in every direction.

B. *Specifications*

Now some details about the size and power capacities are given:

- Dimensions: 4 meters in diameter, 2.5 meters in length, 5mm wall thickness (Aluminum). The structure thus has a mass of 2,500 kg.
- Required power: 120 kW.
- Uses new generation of solar arrays with 125 W/kg. Mass of 960 kg + 120 kg of structural connection.
- 5 kW need to be rejected. Radiators can reject 350 W/m^2 with a mass of 12 kg/m^2. Mass of 360 kg + 60 kg of structural connection.
- Water recycling system: 500 kg (result given by the Human Aspects group).

That gives us a total dry mass of 4500 kg for the SM. The launch mass will be around 10 tons which includes 5 tons of Xenon fuel and 500 kg of water.

The solar arrays will be retractable and for launch the total diameter will be 4.8 meters which we can still fit in the payload bay of the launcher. Another feature of the solar arrays is that they have joints with small electrical motors so that they can always point in the direction of the sun and produce the maximum power possible at every time.

Another point to mention is that the SM is not designed to live in. It is only designed for a really short stay ($<$ 2 hours) inside, e.g. if there is a failure with one of the power systems. That is why it does not contain full life support systems and no special radiation protection.

C. *Electric propulsion*

The purpose of the electric propulsion fitted on the Storage Module (SM) is to transport the completed structure from Low Earth Orbit to the chasing orbit at 33 000 km. The amount of chemical propellant required to transport this structure would be an order of magnitude greater than what electric propulsion is able to do. The time it takes to transport the structure is greater when using electric propulsion, but this is not an issue as humans will not be on-board for this journey. The other purpose is to transport the SM and Launch and re-Entry Vehicle (LEV) to the chasing orbit when the crew has departed for GEO. This way the SM is able to match orbits with the Mission Module much easier when the crew returns in the Mission Module from GEO.

The thruster selected for the electric propulsion is the X3 Ion Thruster, see figure 10. The X3 is a Hall-effect Ion Thruster, developed by the University of Michigan, NASA and the United States Air Force as a joint project. The X3 is the most advanced and most promising electric propulsion option available. The X3 has a effective exhaust velocity of 30000 m/s giving it a specific impulse of 3058 s in vacuum. The weight of one thruster is approximately 100 kg for the 2.7 N version. Four of these thrusters will be fitted on the Storage Module so that two thrusters are on the same side of the spacecraft. The thrust for one thruster is approximately 2.7 N, total of 5.4 N for one direction and power of 100 kW per direction. The thruster is developed to be used for transportation in space in cases where time is not as essential as the cargo capacity of the transport. [8]

The thrusters use Xenon as propellant. The maximum capacity for propellant is 4 tonnes which gives approximately 5500 m/s ΔV, enough for the transfer from LEO to chasing orbit in 33 000 km and two missions after this. These calculations are valid for a vehicle with a dry mass of 20,000 kg and wet mass of 24,000 kg, which is the configuration from LEO to chasing orbit. The power for the thrusters comes from the solar arrays fitted on the Storage Module, rated for 120 kW of power which is divided between the life support systems and thrusters. The thrusters will generate heat which needs to be managed but

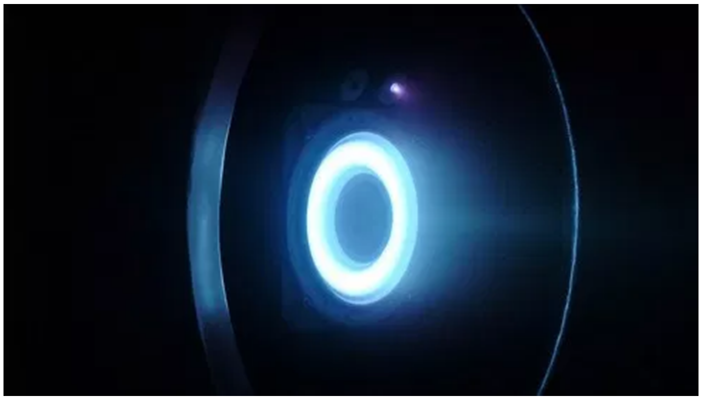

Fig. 10. X3 Ion thruster [8]

TABLE IV
SPECIFICATIONS OF THE ELECTRIC THRUSTER

Characteristic	Value
Thrust	2.7 N
Propellant	Xenon
Vacuum ISP	3058 s
Veff	30000 m/s
Mass flow rate	0.00009 kg/s
Dry mass	100 kg

there is no humans aboard the vehicle when the thrusters are fired, temperature management for living conditions is not as critical.

The specifications are gathered in table IV.

V. Mission Module and airlock

The mission module is the vehicle providing living and servicing needs to the crew. With airlock and service module, it goes to the targets, performs the tasks, and supports the crew members through out the mission at GEO. It initially will be launched to LEO, then sent to chasing orbit. Since then the mission module and airlock will be traveling only between GEO and meeting orbit, unless emergency mission abort, and be reused as long as the program.

A. Overall design

The mission module is inspired by international space station (ISS) modules, particularly the European lab Columbus [9], in which crew conducts experiments both inside and outside the module. The cylindrical shaped module is able to dock with airlock, host up to three crew members for up to one month, power itself with electricity, and provide engaging tools for servicing including one European robotic arm and two smaller arms outside. To meet the mission requirements but minimise costs, the mission module is redesigned based on Columbus while the airlock is adapted MRM-2 [10] on ISS.

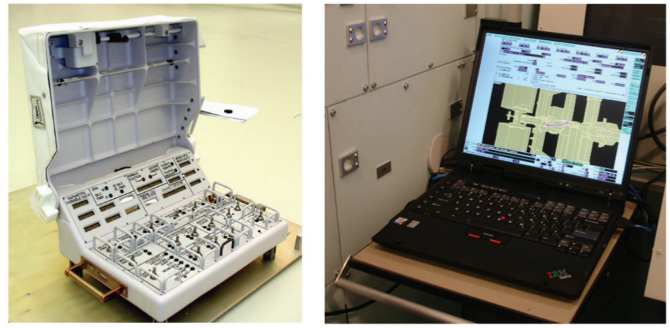

Fig. 11. Man Machine Interface for European Robotic Arm [11]

Using the MRM-2 can potentially reduce costs of redesign a new airlock, and its light weight and small size suits the logistic demands. Specifications of the mission module are listed in table V.

TABLE V
MISSION MODULE SPECIFICATIONS

Mass (kg)	Diameter (m)	Length (m)	Volume (m^3)	Power (kW)
10,000	4	5	44	5

B. Interior

With 44 m^3 pressurised volume, there is sufficient room for crew and equipment. The walls will be occupied by life support systems, control interfaces and payloads. A Control Post [11] with computers will be inside the mission module in order to control the robotic arms on board. The robotic arms can be controlled by crew in the mission module, or by mission control center on ground. Examples of control panels of robotic arms is shown in figure 11.

Considering the radiation condition in GEO where astronauts living in the module, the wall is designed to shield the energy by its outer 4 mm and inner 2 mm thickness of Aluminium combined with 4 mm thickness of water layer in the middle as insulation and absorption material.

C. Exterior

The outside of the module will be mounting solar arrays and radiators. Total power of 6 kW solar cells will be installed and fuel cells are used as redundancy. Power consumption is listed in table VI.

TABLE VI
MISSION MODULE POWER USAGE

System	Power (kW)
Life support system	1.5
Robotic arms	1.5
Circulating system	1
Communication&others	1
Total	5

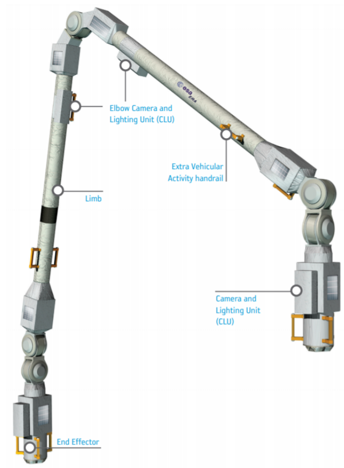

Fig. 12. European Robotic Arm [11]

Apart from that, there are rails circling around both ends of the cylindrical module and connecting together, where the robotic arms are mounted to transfer power and data and able to move all around the exterior in order to fit different servicing needs. The two small robotic arms will be equipped with refueling system or attachment mechanism. On the European robotic arm, an adapted stand can firmly support EVA astronaut. Hand rails are also available on robotic arms, mission module and Airlock. European robotic arm is visualised in figure 12.

Communication and navigation instruments are installed on the mission module, including cameras, antennae, sensors and RCS. The reason to mount the systems on mission module rather than mission service module is that the mission module will be reused while the service module will be one time used (if not refuelled). The exterior layout is illustrated in figure 3.

VI. Service modules

As stated previously, the service modules contain the main chemical propulsion systems and ensure the biggest ΔV required for the missions. These are respectively for the Mission Service Module (MSM) and LEV Service Module (LSM) that travels between chasing orbit and GEP (and back) and the return to Earth from the parking orbit (at 25,000 km of altitude).

A. Overall design and role

Both modules are inspired by the European service module from the Orion spacecraft that is set to launch in the coming years [2] apart from the fact that it only includes engines and propellant tanks. Power and Life Support Systems are contained in other vehicles throughout the mission (LEV, Storage Module and Mission Module). This allowed to achieve a very high wet-to-dry ratio (more on that later).

In order to reduce the costs and complexity of the mission, it was intended to design these modules with very similar characteristics and only to adjust the fuel quantities if required. Even though the modules do not carry the same tasks in terms of ΔV and especially transported mass, the fact that going from the parking orbit towards Earth is way more expensive allowed to use the same engines.

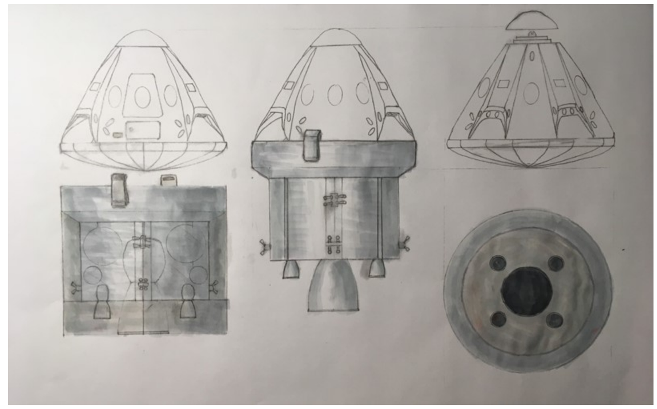

Fig. 13. LSM layout under the LEV

TABLE VII
Space Shuttle Orbital Maneuvering System characteristics

Characteristic	Value
Vacuum Thrust (kN)	26.7
Vacuum ISP (s)	316
Veff (m/s)	3100
Propellant	MMH/N2O4
Mass flow rate (kg/s)	8.6
Size (m), including the nozzle	6.6
Dry mass (kg)	100

Indeed, the MSM's role is to transport the Mission Module (MM) and the Airlock (AL) from the chase orbit to GEO and back to perform the actual mission. This means carrying a lot of mass but with reasonable ΔV (all the numbers are presented in the following section). On the other hand, the LSM only transports the LEV (less mass) but on a greater distance, which means at a greater cost in terms of ΔV.

In terms of overall layout, the MSM and LSM, of which the positions can be seen on the previous overall sketch of the station, respectively docked to the MM and the LEV, are visible on figure 13.

What can be observed is the main nozzle, which is retractable (a technology that exists today on the Vulcain engine from Ariane 5 for example) in order to fit in the payload fairing during launch. There are also other small nozzles and RCS thrusters (not visible) in order to change directions and attitude.

B. Engine and calculations

The main engine used for both modules is the same as for the Orion Service Module, a Space Shuttle Orbital Maneuvering System, whose characteristics are summed up in table VII.

As the same engine as the Orion SM is used, one can wonder why the vehicle itself was not used in the design.

TABLE VIII
SYMBOLS MEANING

Symbol	Meaning	Unit
T_{tot}	Total thrust	N
ISP_{vacuum}	ISP in vacuum	s
V_e	Exhaust velocity	m/s
V_{eff}	Effective velocity	m/s
m_e	Mass flow rate	kg/s
p_e/p_a	Exhaust/Atmospheric pressure	Pa
A_e	Nozzle exhaust area	m
m_f/m_i	Final/Initial mass	kg

TABLE IX
ΔV FOR EACH PHASE

Propulsion system	Phase	ΔV (m/s)	Modules to carry
MSM	33000 to GEO	109	MM + AL + MSM
MSM	Mission	41	MM + AL + MSM
MSM	GEO to 25000	381.3	MM + AL +MSM
LSM	25000 to Earth	1489	LEV + LSM

The reason is simple, the Orion spacecraft maximal ΔV is only 1,700 m/s [2], which is not sufficient for the envisioned mission (and any GEO mission if not using the last stage of the future Space Launch System from NASA which does the injection from LEO). Thus, a reduced mass was achieved through the conception of these modules which fit perfectly the proposed tasks.

Regarding propellant consumption, the following equations are used, assuming constant mass flow rates, exhaust pressure and vacuum conditions.

$$\text{Total thrust: } T_{tot} = m_e \cdot V_{eject} + (p_e - p_a) \cdot A_e = m_e \cdot V_{eff} \quad (1)$$

$$\text{Vacuum ISP: } ISP_{vacuum} = \frac{V_{eff}}{g_0} \quad (2)$$

$$\text{Delta V: } \Delta V = -V_{eff}.ln(\frac{m_f}{m_0}) \quad (3)$$

Now, the values provided by the Logistics team for the ΔV are gathered in table IX.

In order to determine the propellant required and if the service modules can effectively achieve the required ΔV, the mass of all the modules are needed. They are compiled in table X.

As stated previously, the wet to dry ratio achieved here is very high, implying in a way that technology advances in regards to fabrication and mass of materials are expected in the coming years.

TABLE X
MASSES OF ALL MODULES

Module	Mass (kg)
MM	10,000
AL	3,500
Dry MSM	1,000
Wet MSM	4,000
LEV	6,000
SM	10,000
Dry LSM	1,000
Wet LSM	5,500

TABLE XI
PROPELLANT CONSUMPTION OF THE SERVICE MODULES

Module	MSM	MSM	MSM	LSM
Phase	33000 to GEO	Mission	GEO to 25000	25000 to Earth
Mass ratio	0.97	0.99	0.88	0.62
Initial mass (kg)	17500	16895	16673	11500
Final mass (kg)	16895	16673	14743	7114
Prop. used (kg)	605	222	1930	4386
Prop. left (kg)	2395	2173	244	114

With these values, it can now be shown that the proposed service modules can indeed achieve the required transfers. All results are summed up in table XI.

The way this table is completed is the following. First, the mass ratio required to achieve the ΔV for each phase is calculated, using a constant V_{eff} (assuming vacuum conditions, thrust and mass flow rate remain the same). Then, the initial mass works as an input to obtain the final mass. The difference between those two is the propellant consumption for each phase. The calculations are done using equations 1, 2 & 3. In the end, there is some extra propellant remaining, it encompass small directions or attitude maneuvers that were not calculated explicitly here. However, there is not enough left to perform additional missions so both service modules have to be changed after every mission (or at least refuelled, which has not been done in space for chemical propulsion yet).

VII. CONCLUSION

Throughout this project, it has been possible to produce basic spacecrafts design capable of achieving human services in geostationary orbit.

Regarding the limits of this study, the dimensions of the satellites on which the astronauts are supposed to operate services were not considered. It means that there might be coordination issues and a general lack of space near the Mission Module, MSM and Airlock once the satellite is grabbed by the robotic arms. In addition, only having one vehicle with a heat shield capable of entering the atmosphere might be an issue in case of an emergency because the astronauts would first have to dock and change vehicles (see the Logistics group off-nominal case).

One has to keep in mind that every aspect of the conception was not emphasized equally. In this study, the focus has been put on trying to create plausible modules and vehicles, based on existing ones and hoping for technology advances in the next ten years. Nevertheless, propellant consumption, whether it was chemical or electrical has been thoroughly calculated and no too far away in the future assumption has been taken into account. The designed modules and vehicles general specifications are well in line with real future projects, be that in terms of wall thickness, achievable ΔV, robotic arms capabilities etc...

APPENDIX A

Here are provided additional unused sketches of the designed vehicles.

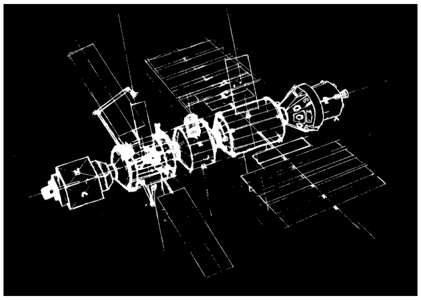

Fig. 14. Full station in black and white

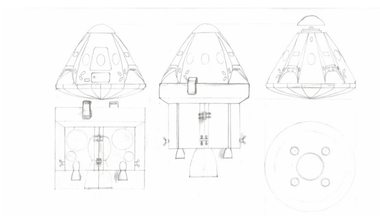

Fig. 15. LEV first design

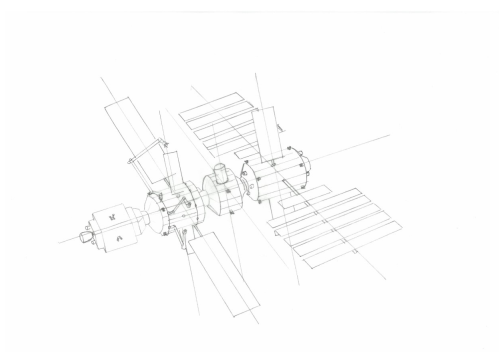

Fig. 16. Launch configuration in black and white

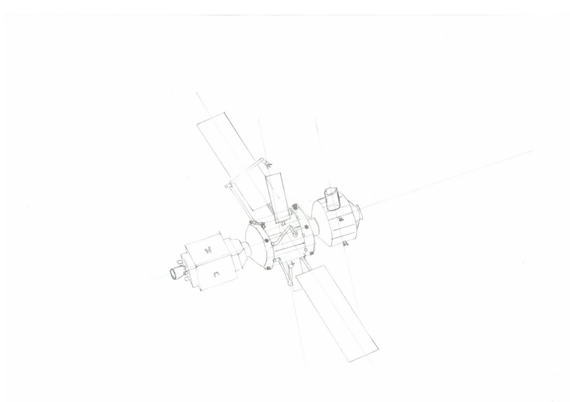

Fig. 17. Mission configuration in black and white

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