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Lunar Orbiter Trade Study and Conceptual Design of Onboard Propulsion System

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In recent years, the lunar explorer programs, suspended for a long time, have resumed again with the rapid development of low-cost, high-level technologies, and hence several nations have made a success of lunar exploration programs with their own developed orbiters. Late in 2007, the Science Ministry of the Republic of Korea announced that Korea planned to send its first orbiter to the moon by the year 2020. The major objective of the present study is to set up a fundamental baseline on which to design an optimal type of onboard propulsion system. To do this, the mission requirements of the Korean lunar orbiter are summarized at first. Next, the mission requirements of various orbiters are surveyed and also an overview of their key design specifications is investigated. Based on the results of this trade study, the conceptual design of the onboard propulsion system of the Korean lunar orbiter is finally discussed with its major key design requirements of the expected propellant quantity, the minimum thrust level for lunar orbit insertion, and the specific characteristics of the necessary components along a whole system schematic diagram.

Nomenclature

g	=	gravity acceleration, m/s^2
I_{sp}	=	specific impulse, sec
M_{fuel}	=	fuel mass, kg
M_{wet}	=	wet mass of the orbiter, kg
ΔV	=	delta-V, m/s

I. Introduction

AFTER the Apollo project's first successful human landing on the moon in 1969, all the lunar exploration programs of the United States were gradually suspended for over 20 years due to the enormous financial expense and a rapid decrease of interest in moon exploration. But after several small lunar orbiters such as Hiten, Clementine, and Lunar Prospector were launched again since the early 1990s, interest in moon exploration has been revived. Lunar exploration programs were restarted though the related activities were low-key compared with the frantic efforts of past decades. Recently, several nations have executed lunar exploration programs successfully, developing their own orbiters, such as the European SMART-1, the Chinese Chang'E-1, the Japanese SELENE, the Indian Chandrayaan-1, and finally the US LRO (Lunar Reconnaissance Orbiter).

Late in 2007, the Science Ministry of the Republic of Korea announced that Korea had established a new roadmap for its National Space Development Program and planned to send the first orbiter to the moon by the year 2020. Although Korea is a late starter in the space exploration field, a dozen commercial and science research satellites have been successfully launched into the earth's orbit in the past decade. According to the ministry's roadmap, the Korean national aerospace research institute will start developing the lunar orbiter and the 1.5-ton launch capacity rocket named KSLV-2 (Korea Space Launch Vehicle-2) together. As a result, Korea started to investigate the feasibilities and the necessary requirements by implementing a planning study of lunar exploration in 2008. From this study, developing an onboard propulsion system of the orbiter is identified as one of the most important issues especially because this will be the first challenge for Korea to make the orbiter arrive correctly at another planet far from the earth.

Hence, the major objective of the present study is to set up a fundamental baseline on which to employ an appropriate type of the onboard propulsion system. To do this, the mission requirements of the Korean lunar orbiter derived from the planning study are summarized at first. Next, the mission requirements of various orbiters are surveyed and also an overview of their key design specifications is investigated. Based on the results of this trade study, the conceptual design of the onboard propulsion system of the Korean lunar orbiter is finally estimated with its major key design requirements of the expected propellant quantity, the minimum thrust level for lunar orbit insertion, and the specific characteristics of the necessary components along a whole system schematic diagram.

II. Overall Mission Objectives and Requirements

Currently, the objective of the Korean lunar orbiter mission is to obtain lunar scientific data, which includes global mapping data of mineralogical compositions, topography, and geological structure, and data of the lunar orbit environment with high accuracy and resolution [1]. Table 1 summarizes the planned payload instruments of the orbiter which are consist of a HRS (high-resolution stereo) camera, a mini SAR (synthetic aperture radar), an x-ray spectrometer, a laser altimeter, and an ion/plasma analyzer. These data will be used to improve the understanding of the moon, and will also be useful for researching the feasibility of future utilization of moon exploration in conjunction with the recent lunar missions of other nations [1].

According to the outcome of the planning study of Korean lunar exploration established in 2008, the key mission requirements for the first Korean lunar orbiter are estimated as summarized in Table 2 [1]. The Korean lunar orbiter will be designed to operate in a 100 km altitude with a 90° inclination of the lunar orbit. Its expected mission life will be at least 1 yr and it will collect valuable data regarding the lunar surface and environments. The orbiter will operate in a three-axis stabilized, nadir-pointed configuration with either reaction wheels or thrusters as the selected control actuator. The reaction wheels will be used for the mapping phase and thrusters will be necessary for maneuvers and unloading of the reaction wheels during the mission. In addition, precise sensors, such as star sensors, gyro, and sun sensors, will be equipped for attitude control of the orbiter. The electrical power will be provided by solar arrays mounted on the orbiter structure. The solar arrays will generate an average power of

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Table 1 Planned payload instruments for the Korean lunar orbiter

Payload instrument	Mission
High-Resolution stereo camera	Produce a high-resolution map
Mini SAR	Perform radar scattering and imaging investigations
X-ray spectrometer	Map the surface mineral composition
Laser altimeter	Measure the surface topography
Ion/plasma analyzer	Analyze orbit environment

Table 2 Key mission requirements for the Korean lunar orbiter

Mission requirements	Parameter data
Launch vehicle	KSLV-2
Mission life	>1 year
Lunar orbit altitude	100 km (circular)
Lunar orbit inclination	90°
Orbiter total mass	<550 kg
Orbiter dry mass	<300 kg
Fuel mass	<250 kg
Payload mass	<50 kg
Average power (EOL)	<400 W
Pointing knowledge	0.01°
Pointing accuracy	0.02°
Nadir pointing stability	0.001°
Stabilization	3-axis
Autonomy operation	2 weeks
TMTC transmission	S-band
Data transmission	Ka-band

400 W minimum at the EOL (end of life) period. As a battery candidate for the orbiter, a lithium-ion battery is now considered due to the best energy-to-weight ratios, no memory effect, and a slow loss of charge when not in use. It is expected that a capacity larger than 40 Ah at EOL will be enough for the orbiter's mission. To maintain the orbiter's internal temperatures within design limits during all mission phases, both active and passive thermal control hardware will be used with radiators, multilayered insulation blankets, and heaters to control temperatures. For the RF communications, S-band frequency will be used to transfer simultaneous commanding, telemetry, and tracking data between the orbiter and the ground station with a gimbaled antenna system, while Ka-band frequency will be for data transmission measured from the orbiter's payload system. A command and data handling system will provide a reliable computing hardware platform for the flight software operation, a mass storage device to save sate-of-health data of the orbiter, a solid state recorder to save data obtained from the payload, and a communication interface for the command, telemetry and data transmission. The onboard PS (Propulsion System) of the orbiter will provide on-orbit attitude control and delta-V (ΔV) adjust burns for all mission phases.

Among the several mission requirements, the most important one is to launch the lunar orbiter using the new launch vehicle, the KSLV-2, which will be developed from 2010 to 2018. According to the outcome of the recent feasibility study for the Korean launch vehicle, the KSLV-2 will be designed to have a capability for inserting 1.5 ton class spacecraft into a sun-synchronous orbit with a 700 km altitude and 95° inclination. Its orbit insertion capability will be able to be increased up to 2.6 ton by using a low-earth-circular orbit with a 300 km altitude and 80° inclination. If a 300 km altitude circular orbit is used as a parking orbit for the TLI (translunar injection), the TLI capability of the KSLV-2 equipped with a TLI stage solid kick motor is estimated as 550 kg [1,2]. As a result, the maximum launch mass of the orbiter is considered to be 550 kg, which includes 250 kg of liquid fuel mass for its onboard propulsion system and 50 kg of mass for the payload system. Further information on the KSLV-2 is summarized in Table 3 [1].

Table 3 Expected performance characteristics of the KSLV-2

Parameter	Characteristic data	Expected configuration
Capacity	1.5 ton class payload	
Orbit altitude	700 km	
Weight	200 ton	
Height	50 m	
No. of stages	3	
First stage	75 ton Engine × 4 EA	
Second stage	75 ton × 1 EA	
Third stage	10 ton × 1 EA	

After launch, the orbiter will be injected into a parking orbit at a 300 km altitude at first, and then the solid kick motor of the TLI stage provided by the launch vehicle will burn to send the orbiter into its translunar injection trajectory. Once the orbiter arrives in the vicinity of the moon, it will begin a sequence of several LOI (lunar orbit insertion) maneuvers with its onboard propulsion system. After completing the LOI sequences, the orbiter will move to a 100 km polar mission orbit of the moon, where it will remain for a minimum of one year, and collect scientific data over the entire lunar surface. A schematic of the expected lunar transfer scenario is illustrated in Fig. 1 [1,2]. A detailed lunar transfer approach is not yet determined, but it should be fixed through considerable trade investigations in the future.

III. Propulsion System Trade Study of Lunar Orbiters

As a specific lunar transfer approach of the Korean lunar orbiter is not yet decided, the selection of the onboard propulsion system candidates is under investigation. To choose an optimal one, it is essential to survey the previous heritages of several of the lunar orbiters launched in recent years. Hence, the key mission requirements of lunar orbiters, such as mass, and TLI transfer approach, and other related characteristics of their onboard PS will be investigated by trade studies in this section. First, the recent heritages of lunar orbiters since 1990 are summarized briefly in Table 4 †[3]. From this, it can be known that a total of eight orbiters have been launched by several nations by 2009 after the mission success of Hiten, which was the first lunar orbiter since the Apollo project's suspension. Especially, five orbiters were launched within the past three years among them, which means a race to the moon has rapidly been restarted. Next, the types of onboard PS and TLI transfer approaches used for the recent lunar orbiters are also listed in Table 4 [3]. Depending on the energy source of propulsion, it reveals that a total of seven orbiters employed a chemical propulsion system and one orbiter, SMART-1, used electric propulsion. For the chemical propulsion system, a mono or bipropellant type has been used individually or combined together. In terms of TLI transfer, a total of four approaches were selected for lunar orbiters. Among them, the phasing loop and the direct injection approaches are preferred mostly for a total of six orbiters while a weak stability boundary and a spiral method were used just one time each.

To investigate a certain correlation between the onboard PS type and the TLI transfer approach in more detail, the characteristics of each TLI transfer approach are overviewed as follows. In general, the Earth-to-moon transfer trajectories can be divided into three major phases: Leaving the Earth, transferring from the Earth to the proximity of the moon, and approaching the moon [2,4]. In the leaving the Earth phase, there are two main ways to launch from the Earth into a transfer trajectory: by direct ascent into the translunar trajectory or by first inserting into an Earth parking orbit and then, after a specified coast time, executing a TLI maneuver. In the transferring from the Earth to the proximity of the moon phase, four major transfer approaches, which are a direct injection, a phasing loop, a weak

†Data available online at http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html [retrieved 06 January 2010].

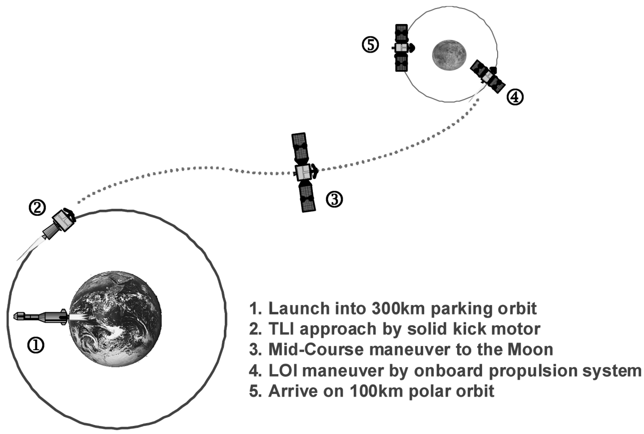


Fig. 1 A schematic of the expected lunar transfer scenario for the Korean lunar orbiter.

stability boundary, and a spiral method, have been devised to date [2,4]. First, the direct lunar injection transfer, such as a Hohmann transfer, has been traditionally used for many lunar missions so far, for example, Luna 1, Luna 9, Apollo 11, Lunar Prospector, and the latest launched LRO [5,6]. The advantages of this transfer are well known as it is the most proven approach from several applications, and can provide a relatively simple transfer process with an adequate performance at the lowest overall cost and risk. Also, it usually takes just four to five days to complete the transfer, which gives a faster way to the moon than other approaches [7]. Next, a phasing loop transfer can get the orbiter to a translunar injection by raising the orbit gradually from the low earth parking orbit to the distance of the nearby moon. To do this, a huge amount of a velocity change (ΔV) must be provided with the orbiter at the parking orbit's apogee point for several times using the orbiter's own main engine or the launcher's upper stage engine. Hence, an AKE (Apogee Kick Engine) using a liquid fuel, which can provide a thrust capability of hundreds of newtons, is generally employed as the orbiter's main engine to raise the orbit. It can operate with several burns unlike a solid kick motor. Clementine, SELENE, Chandrayaan-1, and Chang'E-1 used a 2.5 or 3.5 phasing loop before the final transfer from the Earth to the moon [8–11]. This approach can provide a chance to verify the operating condition status of the orbiters and correct any anomalies before the orbiter arrives at the moon, while it requires additional fuel due to multiburns of a liquid AKE and more operational complexities than the direct injection. In general, it takes two to three weeks to complete transfer [7]. A WSB (Weak Stability Boundary) transfer takes the orbiter to the region of the Lagrangian points of the Earth–sun system to reduce the velocity requirement by arriving at the moon with a low relative velocity. A small maneuver within such a region can lead to a significant change in the lunar arrival conditions. This approach usually has a complex mission design requiring a very precise targeting and control of the flight path. The WSB transfer used for Hiten involved crossing the sun–Earth WSB at a distance of about 1.4 million km from Earth, where the solar perturbation could substantially increase the translunar orbit energy, i.e., increase the perigee too close to the Earth-moon distance [2,12,13]. Finally, the spiral approach requires the longest transfer period than the others. Hence, the electrical propulsion system is a proper way for this approach to save a considerable amount of fuel consumption, but it consequently needs an oversized electric power system [7]. SMART-1 used a low-thrust hall thruster as the main engine to transfer from a geostationary transfer orbit to the lunar orbit over a period of 16 months. Its TLI formed a spiral orbit to elongate its Earth orbit and used three lunar resonance maneuvers to minimize propellant use [14]. The overall characteristics of the TLI transfer approaches are summarized in Table 5 [1,2].

As a result, when considering the used onboard PS types and the TLI transfer approaches together from Table 4, it can be predicted that an electric propulsion system would be an optimal type for the spiral transfer approach only while the chemical PS can be used for other TLI transfer approaches broadly.

Besides the TLI transfer approaches, other mission requirements related to the onboard PS configuration of the recent lunar orbiters can be categorized with the types they used, a monopropellant, a bipropellant, a dual mode, and an electrical system, and then listed in Table 6 [5,6,8–11,13,14].

In the first category, the three orbiters, Hiten, Lunar Prospector, and LRO, have used a monopropellant PS type for their TLI and LOI maneuvers since 1990 [5,6,13]. They all used liquid hydrazine (N_2H_4) as a fuel. Especially, Hiten delivered a relatively small quantity of fuel (42 kg) while the other two orbiters stored more than 100 kg. This is because Hiten got to the moon by a WSB approach to realize a low energy transfer in the TLI phase while the other two orbiters were flown by a direct injection as presented in Table 4. The monopropellant is known for its advantages of high stability,

Table 4 Characteristics of the recent lunar orbiters since 1990

Lunar orbiter	Nation	Launch year	Onboard PS	TLI transfer approach
Hiten	Japan	1990	Mono-Propellant	Weak stability boundary
Clementine	USA	1994	Hybrid mode	Phasing loop
Lunar prospector	USA	1998	(Bi and Mono)	Direct injection
SMART-1	Europe	2003	Mono-Propellant	Spiral
SELENE	Japan	2007	Electric	Phasing loop
Chang'E-1	China	2007	Dual mode	Phasing loop
Chandrayaan-1	India	2008	(Bi and Mono)	Phasing loop
LRO	USA	2009	Bi-Propellant	Direct injection

Table 5 Comparison of TLI transfer approaches

Parameter	Direct injection	Phasing loop	WSB	Spiral
Mission design complexity	Simple	Simple	Various	Complicated
Duration	<1 week	$2 \sim 3$ weeks	$3 \sim 4$ months	>6 months
LV insertion orbit	LEO	GTO/HEO	Lagrangian point	GTO
Launch window	Limited	Expandable	——	——
PS type	Bi- or Mono-Prop	Bi-Prop	Bi- or Mono-Prop	Electrical
Electrical power size	Average	Average	Average	High
Van–Allen belt passage times	1	$2 \sim 3$	1	Several
Disadvantages	Narrow launch window	Complex orbit operation	Communication coverage	Damage by radiation

Table 6 Mission requirements of lunar orbiters based on the type of onboard PS

Lunar orbiter	Mission life, years	Total mass, kg	Dry mass, kg	Fuel mass, kg	Fuel/oxidizer	Thruster size and quantity	Trans-Lunar trajectory insertion
Mono-Propellant type							
Hiten	3	197	155	42	N_2H_4	23 N(8 EA)	Direct ascent by LV
Lunar prospector	1	296	158	138	N_2H_4	3 N(4 EA)	By solid kick motor
LRO	1	1965	1067	898	N_2H_4	22 N(6 EA)	Direct ascent by LV
Bi-Propellant type							
Chang'E	1	2350	1030	1320	MMH/MON-1	10 N(14 EA)	By liquid kick engine (490 N)
Chandrayaan	2	1304	503	798	MMH/MON-3	22 N(8 EA)	By liquid kick engine (440 N)
Dual mode type (including hybrid mode of a bi- and a monopropellant)							
Clementine	1	424	174	195 (bi); 56 (Mono)	MMH/NTO (Bi); N_2H_4 (Mono)	22 N(2 EA) 4 N(10 EA)	By solid kick motor and liquid kick engine (490 N)
SELENE	1	2885	1705	1180	N_2H_4/MON-3 (Bi); N_2H_4 (Mono)	20 N (12 EA) 1 N(8 EA)	By liquid kick engine (500 N)
Electric type							
SMART-1	>1	367	285	82	Xe	70 mN(1 EA)	Direct ascent by LV

simplicity, and reliability of the propulsion operation at a low cost; on the other hand, it uses more fuel consumption due to a low specific impulse characteristic [15]. Hiten's propulsion and attitude control were provided by eight 23 N and four 3 N hydrazine thrusters each. For the Lunar Prospector, a solid kick motor of TLI stage was ignited to send it into TLI trajectory after it was first inserted into about 200 km parking earth orbit by a launch vehicle. Then, LOI burns and attitude control were performed with six 22 N thrusters. For LRO, it entered into lunar orbit with four 80 N thrusters and attitude control was done with eight 20 N thrusters after it was inserted into the translunar trajectory by the Atlas V401 launch vehicle directly. In the second category, Chang'E-1 and Chandrayaan-1 employed a bipropellant onboard PS to use a liquid AKE in their phasing loop transfer [10,11]. The bipropellant PS has some advantages in requiring relatively small fuel consumption and a high thrust level because a liquid AKE can be operated to produce ΔV for multiple times [15]. As Chang'E-1 and Chandrayaan-1 needed a minimum of 2 times of ΔV burns during a phasing loop, 400 N grade bipropellant liquid AKE's were adopted to each orbiter rather than a monopropellant one as seen in Table 6, although a bipropellant type has a high cost and complexity of the orbiter management. They all used liquid MMH (Monomethylhydrazine) as a fuel and a kind of liquid MON (nitrogen tetroxide) as an oxidizer. Approximately 1000 kg of a fuel was supplied to each orbiter, which was mostly used for liquid AKE burns during the phasing loop. For LOI and attitude control maneuvers, fourteen 10 N bipropellant thrusters were employed for Chang'E-1 and eight 22 N for Chandrayaan-1. In the next category, a dual mode propulsion system is reviewed. A dual mode system indicates such a propulsion system that combines the high efficiency of a bipropellant AKE with the reliability and the simplicity of monopropellant thrusters by sharing a common fuel [15]. A hybrid mode of a bi and a monopropellant system combined individually is regarded as one of the dual mode for convenience in this paper because the operating objective and overall configuration of the hybrid mode PS are identical to the dual mode except for using different fuel. Therefore, it can be considered that Clementine and SELENE adopted dual mode propulsion systems of a bipropellant AKE and monopropellant thrusters [8,9]. The dual mode PS of each orbiter provided a high ΔV at a high thrust through a liquid AKE during the initial high-impulse orbit-raising maneuvers in the phasing loop transfer. For Clementine, a STAR37FM solid kick motor and a 490 N bipropellant AKE operated with MMH/NTO were combined together while SELENE used one 500 N bipropellant AKE supplied with $N_2H_4/MON\text{-}3$. After these orbiters arrived on the lunar orbit, then the dual mode system conducted a pulse mode attitude control precisely with a small thrust provided from monopropellant thrusters. In detail, two 22 N and ten 4 N monopropellant thrusters were employed for Clementine, and also 12 20 N and eight 1 N thrusters were for the SELENE orbiter. This system can use merits of both the bi and the monopropellant systems, but it also has additional increases in the total cost and the complexity of the system. In the last category, an electrical PS was equipped as the main engine of SMART-1 [3]. A plasma hall-effect thruster used Xe (Xenon) gas as a fuel by ionizing the Xe, accelerating and discharging the plasma from the orbiter at high speed. A thrust of 70 milliNewtons with a specific impulse of 1600 sec was produced with a total 82 kg of Xe only. Although this electrical thruster was very efficient for fuel savings, roughly 75% (about 1300 W) of total amount of electrical power, 1850 W generated from two large 14 m solar arrays, was consumed to run this thruster during only the flight. Also, SMART-1 took approximately 16 months to enter a lunar orbit by using the spiral transfer approach, which took much longer than the other orbiters. From the above trade study, it can be inferred that selecting which type of onboard PS will be used is dependant mainly on which kind of TLI transfer approach will be employed. For example, a monopropellant type is preferred for a direct injection and a WSB, while a bipropellant or a dual mode is proper for a phasing loop approach, and an electrical type is an optimal one for the spiral transfer. Especially for the phasing loop, the onboard liquid AKE should be required for a translunar trajectory insertion while other approaches are inserted directly by a launch vehicle or a solid kick motor additionally provided to the orbiter. Also, a 500 N grade bipropellant AKE and a 20 N grade monopropellant thruster are most preferred for a chemical propulsion system. In case a precise attitude control is required for the lunar orbit, a small monopropellant hydrazine thruster with less than 5 N thrust would be optimal rather than a bipropellant type, which generally produces more than a thrust of 10 N.

IV. Conceptual Design of Onboard Propulsion System

Based on the current mission requirements of the Korea lunar orbiter and the trade studies for recent orbiters overviewed in previous sections, the conceptual design of the onboard propulsion system of the Korean lunar orbiter will be finally estimated in this section with the major key design requirements of the expected propellant quantity during mission lifetime, the minimum required thrust level for insertion into the lunar orbit, and the specific characteristics of the necessary components with a whole system schematic diagram.

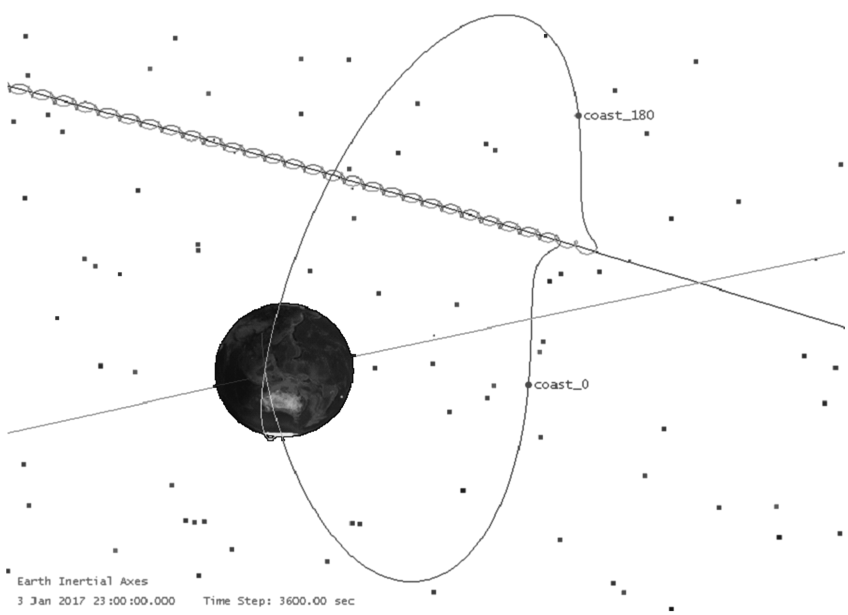
A. Selection of a Propulsion System Candidate

According to a new roadmap of the National Space Development Program, the key development philosophies of the Korean lunar orbiter are summarized as follows [1]: 1) compact size, 2) lightweight, 3) cost-effective technologies, 4) launch by the KSLV-2, and 5) maximum application of satellite technologies obtained from national space programs.

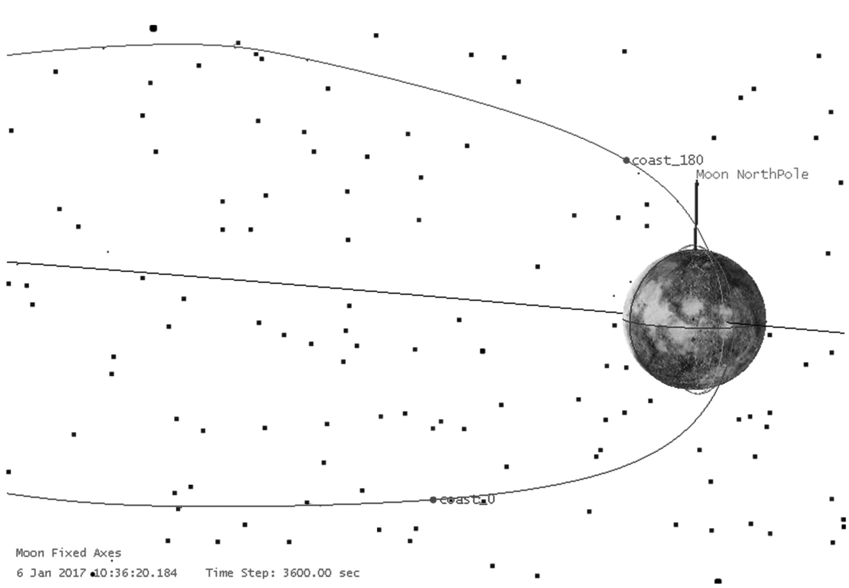
Since the first satellite launch in 1992, Korea has made remarkable progress in the development of a small satellite with 100-kg class and a mid size satellite with 1000-kg class for LEO (Low Earth Orbit). Hence, it is expected that the first three key design philosophies will be achieved without severe difficulties based on our technical experience. Regarding the fourth design philosophy, the KSLV-2 will be used to inject the orbiter into a 300 km parking orbit, and then the solid kick motor of the TLI stage provided by the KSLV-2 will burn to send the orbiter into a TLI trajectory by producing about 3100 m/s of ΔV. Hence, based on the onboard PS and TLI transfer approaches of recent lunar orbiters in Table 4, the direct injection of Lunar Prospector or the phasing loop transfer of Clementine can be regarded as a more appropriate TLI transfer candidate for the Korean lunar orbiter rather than a WSB and a spiral transfer. For a monopropellant type, all technical infrastructures from the system design/analysis phase to the assembly, the integration, and the test phase have been established in Korea for LEO midsize satellite applications over 15 years while the development of a bipropellant system for a GEO satellite still remains at a fundamental level with no sufficient technology experiences, and is thus not commercialized yet. Consequently, to make the maximum application of satellite technologies obtained from national space programs, a direct injection TLI transfer based on the monopropellant propulsion type as that of Lunar Prospector in Table 6 would be considered as the most optimal candidate system for the Korean lunar orbiter. By doing this, all other key development philosophies can be satisfied at the same time in terms of the current national capabilities of technology, a schedule, and a budget as a monopropellant system has general advantages of high stability, simplicity, and reliability combined with a low cost [15]. Therefore, the USA tends to employ a monopropellant-based propulsion system recently for Mars explorer spacecraft, for example, Mars Exploration Rover, Mars Reconnaissance Orbiter, and Phoenix Mars Lander, to reduce the complexity of the propellant management after the failures of Mars Observer and Mars Climate Orbiter [16,17]. An expected direct injection trajectory for the Korean lunar orbiter is illustrated in Fig. 2 with different axes [1].

B. Estimation of a Fuel Budget

To estimate a fuel budget, required ΔV values for a direct injection transfer calculated approximately from the planning study report [1] are considered with a following Tsiolkowski's Eq. (1) [15]. Here, total wet mass of the orbiter M_{wet} is assumed as 550 kg, and an



a) Based on Earth internal axes



b) Based on Moon fixed axes

Fig. 2 Expected direct injection trajectory for the Korean lunar orbiter.

Table 7 Delta-V and fuel consumption estimation

Maneuver	Delta-V, m/s	Fuel mass, kg	Ratio, %
Trajectory correction #1	38.2	9.6	3.9
Trajectory correction #2	8.2	2.0	0.8
Trajectory correction #3	2.5	0.6	0.2
Lunar orbit insertion #1	447.0	100.6	40.2
Lunar orbit insertion #2	240.4	46.1	18.4
Lunar orbit insertion #3	182.0	31.6	12.6
Mission orbit insertion	50.0	8.2	3.3
Orbit station-keeping	150.0	23.6	9.4
Subtotal	1118.3	222.4	89.0
Max. Allocation	——	250.0	100.0
Margin	190.0	27.6	11.0

expected specific impulse of the onboard PS is $I_{\mathrm{sp}} = 220$ s, which is a generally known data for a monopropellant hydrazine thruster [15]

$$M_{\mathrm{fuel}} = M_{\mathrm{wet}} \times \left[1 - \exp\left(-\frac{\Delta V}{g \times I_{\mathrm{sp}}}\right)\right] \tag{1}$$

The estimated ΔV and the fuel consumption of each maneuver are summarized in Table 7. As a result, it is presumed that a total 222.4 kg of hydrazine fuel will be required to get ΔV of 1118.3 m/s. As this estimation fully satisfies a maximum allocation of fuel quantity of 250 kg, the remaining 27.6 kg can be secured as a margin with 190 m/s of ΔV. From the fuel ratio of each maneuver in Fig. 3, it can be estimated that a fuel budget is dominated by the sequence of LOI maneuvers that put the orbiter into its desired orbit around the moon. A considerable quantity about 178 kg of 250 kg fuel (71%) will be required for three-stage LOI phases. Among them, about 100 kg of 178 kg fuel (56%) will be consumed for LOI #1 maneuver that provides the required ΔV to allow the orbiter to be captured by the moon's gravitational field.

C. Estimation of LOI Thrust Level

When the orbiter arrives near the moon, it will need to execute successful LOI maneuvers to stably enter a lunar orbit. As these LOI burns are mission critical, several steps shall be taken to maximize the overall flexibility and probability of success. To do this, an appropriate level of LOI thrust is estimated simply by comparing with the burn duration of the insertion thruster of Lunar Prospector and LRO's cases because further requirements are still under investigation. The detailed investigation results are summarized in Table 8. For Lunar Prospector, a total thrust of 44 N was delivered by two 22 N thrusters during a 74-minute burn. LRO used four 88 N insertion thrusters to get 352 N, and operated for a total of 68 min for the LOI maneuver [5,6]. From these two orbiter's heritages, it can be predicted that roughly a 70-min burn duration would be sufficient to complete a LOI maneuver. After conducting trade studies with different thrusts,

Table 8 Burn duration comparison of LOI thruster

	Lunar prospector	LRO	Korean lunar orbiter		
LOI thrust level	44 N	352 N	44 N	88 N	132 N
Maneuver	LOI thrust burn duration, min				
LOI #1	33	45	82	41	27
LOI #2	22	12	38	19	13
LOI #3	19	8	26	13	9
LOI #4	——	3	——	——	——
Total	74	68	146	73	49

such as 44, 88, and 132 N provided by a combination of multiple 22 N thrusters, it is found that approximately a force of 88 N can make the orbiter execute a desirable LOI maneuver if the insertion thruster burns for 73 min. For an application of a 44 N thrust, the orbiter may not be captured sufficiently by the moon's gravitational field with a slow LOI phase or it may crash against the moon's surface due to a rapid LOI with a force of 132 N.

D. System Level Conceptual Design

From these investigations, a type of onboard PS, a fuel budget, and a LOI thrust level have been estimated. Based on these estimates, two conceptual schematics for the onboard PS are proposed in Fig. 4. Basically, they consist of the main components such as fuel tanks, fill/drain valves, pressure transducers, filters, latching isolation valves, interconnecting fuel lines and thrusters without redundant nature. The first type proposed in Fig. 4a is an unregulated pressure mode (blowdown), which is pressurized to an initial level, and the pressure is allowed to decay as fuel is used. The general advantages of the unregulated pressure type are that it is the simplest, more reliable and less expensive because of fewer components, while a tank pressure, a thrust, a specific impulse and a fuel rate vary as a function of time [15]. The second type is a regulated pressure mode which controls the pressure in the tanks at a preset pressure level. As proposed in Fig. 4b, the pressurant gas is stored in a separate tank at a high pressure level, and additional regulator and flow valves are incorporated to controls the pressure precisely. Hence, additional mass budget should be considered from the initial design phase. Another disadvantage is the increase complexity of a pressure control than the unregulated mode. But this regulated mode can produce a constant value of a thrust during fuel consumption because the fuel is supplied at a tightly controlled pressure level to LOI thrusters [15].

To guarantee the high-functional system reliabilities and minimize program risks, most components, which have been flight qualified on the heritages of the previous planet orbiters and Korea Multi-Purpose Satellite (KOMPSAT) programs, were selected carefully. The specific list of the PS component candidates is provided in Table 9. For a fuel tank, it is required to store 250 kg of a liquid hydrazine in monopropellant or high purity grade per MIL-PRF-26536.

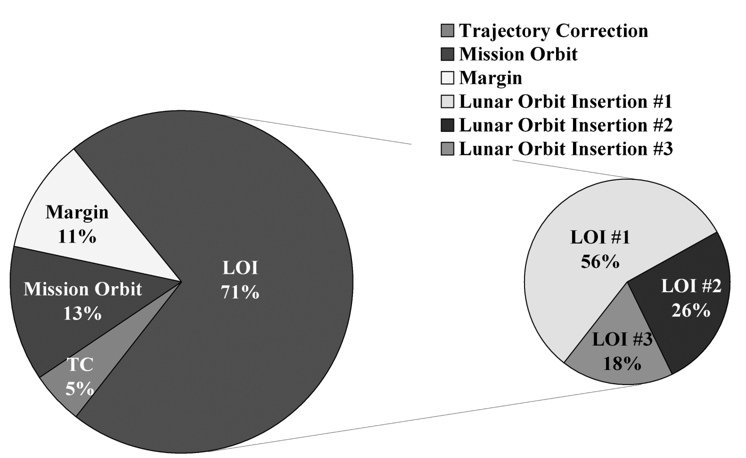
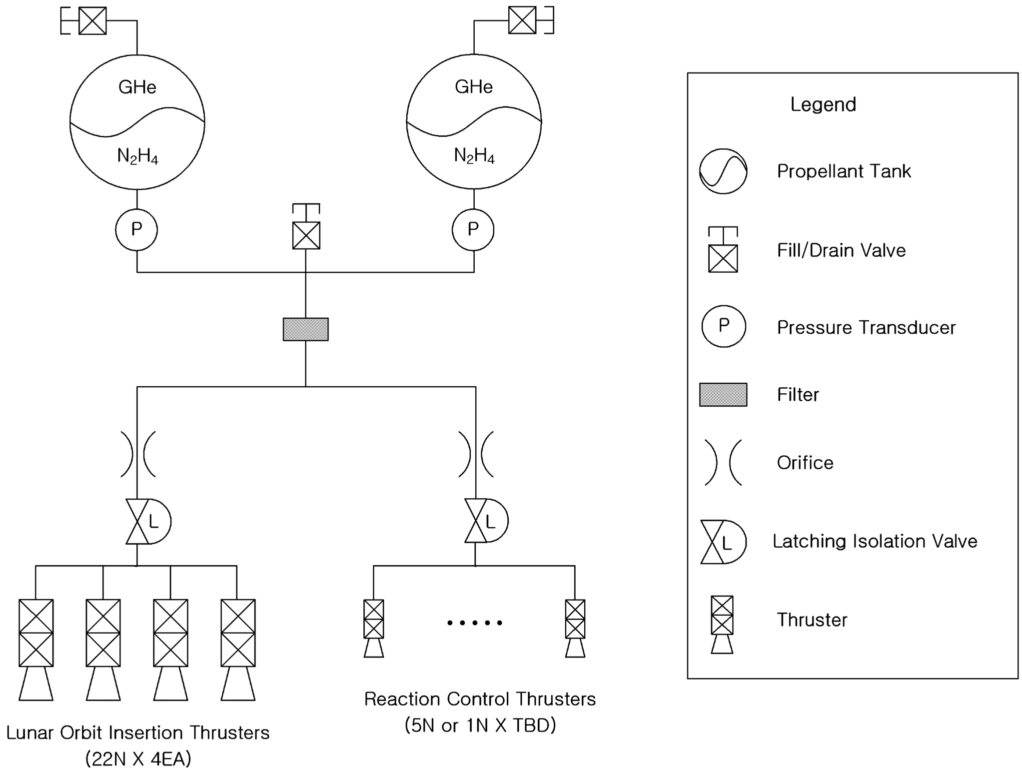
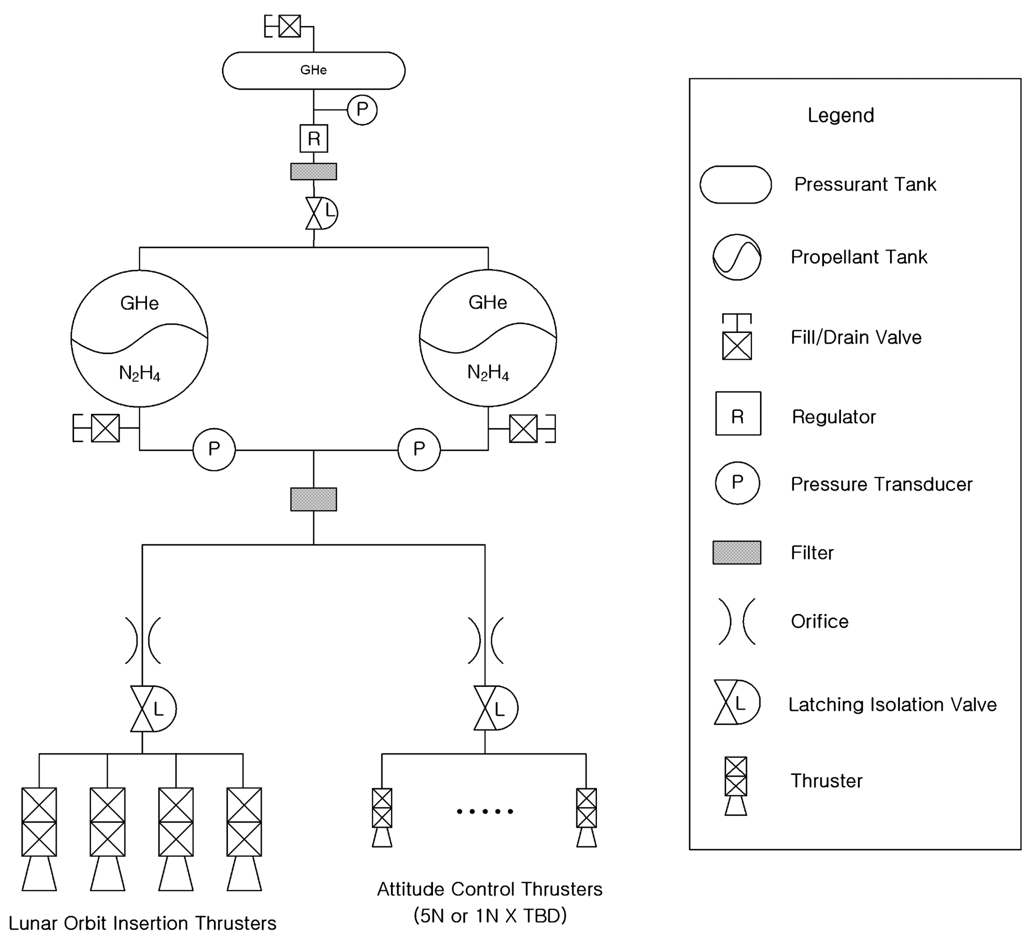


Fig. 3 Estimated fuel ratio for each maneuver.



a) Unregulated pressure mode (Blowdown)



b) Regulated pressure mode

Fig. 4 Conceptual schematics of the onboard PS for the Korean lunar orbiter.

Table 9 Major propulsion component candidates for the Korean lunar orbiter

Component	Main requirement	Quantity (EA)	Heritage
Fuel tank	250 kg hydrazine at 350 ~ 450 psia, titanium, spherical, blowdown	2	Magellan, Cassini
Pressurant tank	Max. 3 kg helium gas at3500 ~ 4500 psia, composite overwrapped pressure vessels	1 (Regulated type)	To be developed
Fill/drain valve	Incorporate redundant seals in series	3	KOMPSAT
Pressure transducer	An input voltage of 22 to 34 Vdc and provide an output voltage of 0 to 5 Vdc @ 350 ~ 450 psia	2 (Unregulated type) 3 (regulated type)	Lunar prospector, KOMPSAT
Filter	Incorporate 15 μm filtering capacity	1 (Unregulated type) 2 (regulated type)	Lunar prospector, KOMPSAT
Latching isolation valve	Incorporate a latching mechanism to retain in the open and closed position without an electrical power	2 (Unregulated type) 3 (regulated type)	Lunar prospector, KOMPSAT
Thruster	22 N grade at 350 ~ 450 psia	4	To be developed
	5 N grade at 350 ~ 450 psia	To be determined	KOMPSAT
	1 N grade at 350 ~ 450 psia	To be determined	To be developed
Thruster Valve	22 N grade at 350 ~ 450 psia, incorporate dual seat solenoid	4	Various
	5 N grade at 350 ~ 450 psia, incorporate dual seat solenoid	To be determined	KOMPSAT
	1 N grade at 350 ~ 450 psia, incorporate dual seat solenoid	To be determined	Various

From preliminary surveys of commercial off-the-shelf products, it is hardly found an appropriate one that can carry 250 kg with only one tank. Hence, it should consider using two tanks in parallel connection as proposed in Fig. 4 system schematics. Each tank can carry a maximum load capacity of about 130 kg fuel at 450 psia operating pressure. This tank is a 28-in. spherical type constructed of 6Al-4V titanium, and a rubber diaphragm is installed inside for a positive fuel expulsion device. The operating performance of this tank was fully qualified by using for the Magellan and the Cassini spacecraft. For the regulated pressure mode type in Fig. 4b, a pressurant gas tank and a regulator will be additionally assembled to the upstream of the propellant tanks in parallel to control the pressure level precisely. For both system mode types, the PS will be pressurized with gaseous helium to between 350 and 450 psia as did for Lunar Prospector and KOMPSAT programs. Also to load the fuel and a gaseous pressurant, total three fill/drain valves will be necessary for both mode types, and they should incorporate in-series redundant seals to prevent a fuel leakage for safety. Two pressure transducers will be installed in the downstream of the fuel tanks to measure fuel supply pressure for each system schematics and provide telemetry signal to the ground station during mission life, while one pressure transducer will be additionally used to check the pressure level of the pressurant gas in Fig. 4b. An output voltage of 0 to 5 Vdc at 350 ~ 450 psia will be produced with an input voltage of 22–34 Vdc. Basically, one propellant filter will be located in the outlet line from the pressure transducers to protect the components from contamination which may exist in the fuel, and additional filter is required for the pressurant gas in Fig. 4b. The filtration rating of the filter will be 15 microns or less absolute. Two flow restriction orifices will be installed for both system schematics to minimize water hammer effect in the PS fuel lines for the LOI thruster and an attitude control thruster side each during the thruster's transient operations. Also, two latching isolation valves will be also installed in each thruster side to protect the system against failed open thruster valves or excessive leakage conditions by providing an isolation capability between the fuel tank and the thrusters for both system mode types and one more isolation valve will be required especially for the pressurant gas only. All the propulsion components will be connected with fuel lines fabricated of 304L seamless stainless steel tubes to prevent from corrosion, erosion and dissolution due to toxic hydrazine, and each joint will be orbital welded with an automatic tube welding machine. For the LOI thruster, total four 22 N thrusters can be optimal to deliver a force of 88 N. Also, a number of 5 or 1 N thrusters will be equipped for lunar orbit maintenance and attitude control in the mission orbit. A required quantity and a thrust level will be determined in detail when the requirements of the attitude control system are fixed. Especially, the current plan is to develop 22 and 1 N thrusters with Korean domestic technologies if possible. Thermal control hardware with heaters, thermostats, and temperature sensors will also be necessary to prevent fuel from freezing in the space environment.

V. Conclusions

The major objective of the present study was to set up a fundamental baseline to employ an optimal type of the onboard propulsion system. To do this, the mission requirements of the Korean lunar orbiter derived from the planning study were first summarized. Then, the mission requirements of various orbiters were surveyed and their key design specifications were overviewed. Based on the results of this trade study, the conceptual design of the onboard propulsion system of the Korean lunar orbiter was estimated with the major key design requirements of the expected propellant quantity of 250 kg during the mission lifetime, the minimum required thrust level with 88 N for insertion into the lunar orbit, and the specific characteristics of the necessary components with a whole system schematic diagram. In future, further research investigations will be conducted to proceed to fix more detailed requirements and a preliminary design of the onboard propulsion system.

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