LILI (Long-term Ice-field Levitating Investigator): A Mars Aerial and Ground Explorer for Glaciers & Polar Ice Fields

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ABSTRACT

The recent discovery of glacier remains in Noctis Labyrinthus, the "Maze of the Night" near Mars' equator sheds new light on the history of water on Mars, the evolution of the planet's climate and geology, and the possibility of life. It also opens the possibility for massive amounts of clean glacier ice to be accessed by astronauts at low latitudes on Mars, alleviating the need to operate in more frigid higher latitudes. Further reconnaissance of the site requires a robotic vehicle capable of traversing rough, salt-crusted glacier surfaces and leaping across crevasse fields. To address this need, we propose a conceptual hybrid aerial/ground vehicle, LILI (Long-term Ice-field Levitating Investigator). LILI combines episodic rotary-wing flight with ground mobility as a propeller-driven sled through an arrangement of skis/runners, wheels, and tilting proprotors. A high-level look at the Noctis Labyrinthus "relict glacier" site is presented, along with a notional LILI mission traverse concept designed to ensure critical scientific measurements are captured. The NASA Design and Analysis of Rotorcraft (NDARC) software is utilized to ensure that mission requirements and sizing constraints are met. Furthermore, future work considers guidance, navigation, and control requirements to satisfy mission objectives, and an initial construction for a simplified LILI small-scale prototype.

NOTATION

BL	buttline, positive right (m)
C_T	coefficient of thrust, $\frac{T}{\rho A V_{tip}^2}$
F_D	drag force (N)
F_F	frictional force (N)
F_N	normal force (N)
F_T	thrust force (N)
F_W	weight force (N)
F_X	x-directional force (N)
g	gravity (m/s^2)
m	mass (kg)
N_b	number of blades
R	rotor radius (m)
SL	station line, positive aft (m)
T	thrust (N)
V_∞	free-stream velocity (m/s)
V_{tip}	tip speed (m/s)
WL	waterline, positive up (m)
σ	solidity, $\frac{N_b c R}{\pi R^2}$
μ_f	coefficient of friction
θ	ground slope (deg)

INTRODUCTION

The exploration of Mars by robotic spacecraft began 60 years ago with the successful flyby of the Red Planet by NASA's Mariner 4 on July 14, 1965. Since then, the planet has been studied by orbiters, landers, rovers, and rotorcraft [Refs.1 and 2]. Orbiters are well-suited for global monitoring and mapping; fixed landers for low-cost in-situ investigations; rovers for higher-cost, heavily-instrumented roaming; and rotorcraft for lightly-instrumented regional exploration. The exploration of ice fields, including glaciers and polar caps, presents unique challenges. The Martian poles were first mapped by NASA's Mariner 9 orbiter in 1972. The polar regions were further imaged and mapped over subsequent decades by NASA's Viking Orbiter 1 and 2, Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter missions, and by ESA's Mars Express and ExoMars Trace

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Gas Orbiter missions. In 1999, the first and, to date, only surface mission to Mars' polar regions was flown. The mission had two components: the Mars Polar Lander and the two Deep Space 2 penetrators, Amundsen and Scott. All were lost: the Mars Polar Lander due to premature engine shutoff, and the DS2 penetrators due to harder-than-predicted impacts. Thus, Mars' polar regions remain unexplored in-situ, in particular because of their extreme environment (esp. thermal) conditions and their extreme, ice-rich terrain.

Meanwhile, ice-rich terrain, including glacier remnants, have also been discovered at several locations at lower latitudes on Mars using the above set of orbital assets. Among these, the "relict glacier" identified in 2023 in Noctis Labyrinthus is particularly intriguing. It implies the presence, at least locally, of clean meteoric H_2O ice in Mars' surface environment near the planet's equator in relatively recent times, which could further enable human exploration of Mars [Refs. 3 and 4]. The site also includes rough terrain and rapid changes in elevation due to deep canyons and a giant volcano.

Vertical-Lift Aerial/Ground Conceptual Vehicles Background

To explore such extreme areas around Noctis Labyrinthus, a hybrid vertical-lift aerial/ground vehicle would be optimal to allow traversing across rough terrain and fly over crevasse fields and wider canyons. The feasibility of flight in the Martian atmosphere was confirmed through the 2020 Mars mission that included both the Perseverance rover and the Ingenuity helicopter, though a combined capability to fly and traverse has yet to be used [Ref. 5]. The use of hybrid vertical-lift aerial/ground vehicles has been explored by Kalantari et al. in 2020 where four independently actuated spherical wheels attached to a UAV allow for traversal over large obstacles [Ref. 6]. Recently, the Mars Sample Return Helicopter concept improved upon Ingenuity's rotor design and incorporated wheels on each of the legs, enabling surface traversal [Ref. 7]. Another vertical conceptual design is the Mars Intelligent Reconnaissance Aerial and Ground Explorer (MIRAGE), which featured a flying-wing configuration with a lift fan for vertical takeoff and landing and a wheel design derived from the Mars Exploration Rovers [Ref. 8].

Schatzman et al. introduced a conceptual design for a Mars aerial and ground explorer of Martian polar regions LILI (Long-term Ice-field Levitating Investigator) with the goal of enabling exploration of regions with harsh terrain and atmospheric conditions [Ref. 9]. This predecessor LILI vehicle leveraged the design of the Ingenuity Mars Helicopter rotor and introduced a hybrid aerial/ground mobility exploration concept where a ski + wheel configuration further enabled navigation through challenging surface conditions. The vehicle from this prior work in ground exploration configuration and in hover is shown in Fig. 1 a) and b).

a) b)

Figure 1. LILI predecessor design configuration in a) ground and b) hover configuration.

Building upon the work in [Ref. 9], the conceptual vehicle proposed in this paper is designed to be mission-specific. We maintain the requirement that the vehicle must be able to travel by both ground and air. In doing so, the vehicle would enable drilling in harsh terrain, where a rover or UAV may be unable to reach. Parameters such as number of rotors and type of ground-traversing mechanism can be modified to best complete mission requirements.

The LILI-type vehicle's capability of both air and ground maneuver could be advantageous beyond exploration on Mars. Such Earth-bound vehicles would be valuable for responding to environmental emergencies, including search-and-rescue operations and certain wildfire-control tasks [Ref. 10]. Additionally, a LILI vehicle's ground-mobility architecture could be modified for water-surface traversal, further broadening the range of potential applications. LILI's approach to exploration could also prove optimal for the in-depth surface exploration of Titan.

RELICT GLACIER

The "relict glacier" found in Noctis Labyrinthus is notable because H_2O ice is currently thermodynamically unstable at the surface of Mars at low latitudes. Consistent with this fact, the "relict glacier" is actually not an exposure of ice at the surface of Mars, but a "light-toned deposit" (LTD) comprising of hydrated and hydroxylated sulfate salts. This LTD, however, presents the distinctive morphologic traits of a glacier, including with crevasse fields, moraine bands, thrust planes, and foliation, suggesting that the LTD is underlain by buried glacier ice [Ref. 4]. The good preservation of the glacier's morphologic traits suggests that both the glacier and its overlying sulfate crust are young, probably late Amazonian in age, i.e., < ~10 Mega-annum old.

The "relict glacier" is nested within the perimeter of a 450-km-wide ancient giant volcano, the Noctis Volcano, discovered only in 2024; see Fig. 2 and 3 [Ref. 11]. A vast and relatively fresh pyroclastic deposit – made of volcanic ash, pumice and scoria – surrounds the "relict glacier" LTD, suggesting the following sequence of events: 1) a glacier forms near the base of the Noctis Volcano, possibly as a result of volatiles released during a recent volcanic eruption; 2) the glacier is subsequently covered by a volcanic pyroclastic deposit produced by an even later stage volcanic eruption; 3) a chemical reaction then takes place between the base of the pyroclastic deposit and the top of the glacier ice, resulting in the formation of a layer of hydrated and hydroxylated sulfate salts; 4) subsequent partial removal of the pyroclastic deposit by erosion reveals the sulfate salts layer, which bears the morphologic traits of the glacier still preserved underneath [Ref. 11].

The thickness of the LTD crust is variable and estimated to range between 1 m and 20 m, with the remains of the possible glacier underneath reaching depths on the order of tens of meters. The surface of the LTD crust is locally extremely rough, with jagged, possibly wind-eroded features reaching in some locations several meters in height. The LTD surface is also dissected in places by crevasse fields, including linear, splaying, circular, and tic-tac-toe crevasses, with surface gaps up to 5 meters across. A few rare, small impact craters less than 100 m in diameter are also found on the LTD.

Such terrain presents insurmountable challenges for a surface rover but could be explored by an aircraft such as the proposed "Nighthawk" Mars rotorcraft concept [Refs. 12 and 13]. However, rotorcraft missions can only carry so much payload, especially when operating at higher elevations, such as at the relict glacier site at + 1.3 km above Mars datum. The LILI mission concept presents an exciting alternative, or a complementary approach to a strict Mars rotorcraft mission. LILI would execute a surface mission with a larger payload mass than allowed by a strict flyer, while still being able to fly over major surface obstacles as would be encountered on the "relict glacier" LTD.

Scientific Impact and Instrumentation

A LILI mission to the Relict Glacier and surroundings would have the following key objectives:

1) Characterize the 3D distribution of H2O and of hydrated minerals.

2) Search for any organics or biosignatures within surface materials.

3) Characterize the geologic evolution of the site, in particular its volcanic history.

4) Assess the site's potential for human exploration, in particular safety, trafficability, and options for in-situ resource utilization (ISRU).

Objectives 1, 3 and 4 would be addressed via a combination of visible color imaging, near-IR spectrometry, ground-penetrating radar (GPR), and neutron spectrometry. Objective 2 would be addressed via near-IR spectrometry and laser-induced luminescence.

A notional science payload on a LILI mission to the "relict glacier" is listed in Table 1 for a total of 10 kg. The mass of some elements of this payload suite is accounted for elsewhere as part of the vehicle's mass: e.g., the imaging cameras are part of LILI's Guidance, Navigation, and Control (GNC) system; the ground-penetrating radar's dipole antennae also serve as LILI's skis.

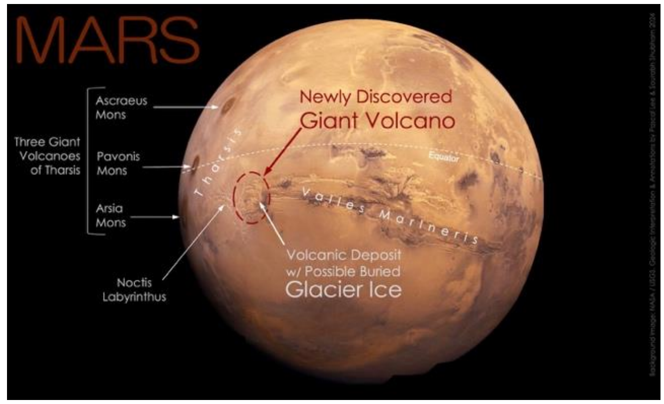

Figure 2. The "Relict Glacier" is located within the perimeter of the recently discovered Noctis Volcano in Noctis Labyrinthus, Mars (NASA & SETI Institute).

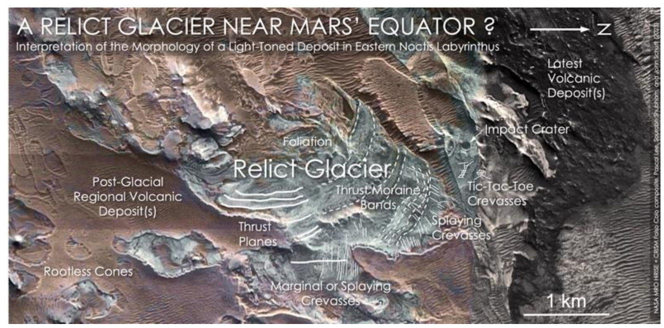

Figure 3. Relict Glacier in Noctis Labyrinthus, Mars. [Figure from Ref. 3]

Table 1. LILI Mission to Relict Glacier: Notional Instrument Payload

Instrument		Comment
OCCAM	Omnidirectional Color Cameras	8 RGB Bayer pattern cameras
NIR	Near-Infrared Volatiles Spectrometer & Radiometer	Heritage: VIPER NIRVSS
GPR	Ground Penetrating Radar	LILI skis used as GPR antennae
NS	Neutron Spectrometer	Heritage: VIPER NSS
OBA	Organics & Biosignature Analyzer	Laser-induced luminescence

In Fig. 4, note that the roving/skiing and flight segments are relatively short, significantly below the maximum ground travel distance of 13.8 km per charge and the maximum forward flight distance of 3.7 km per charge, which is highlighted in the next section.

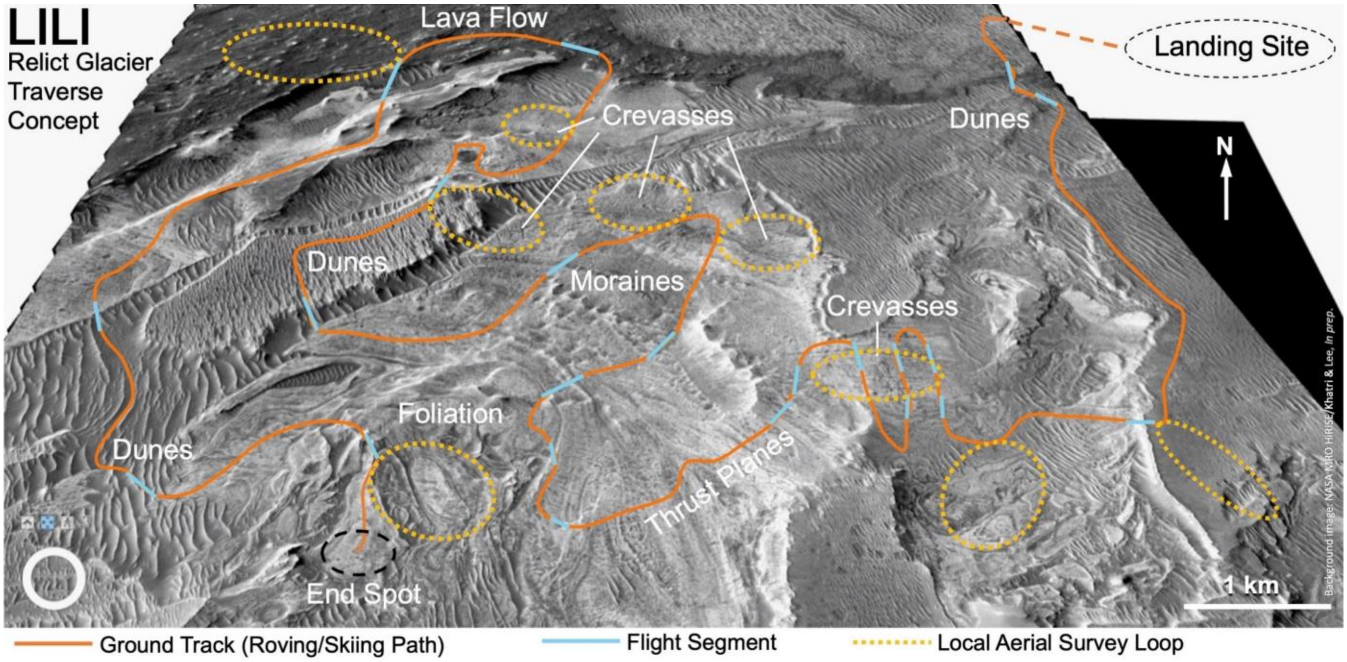

Figure 4. LILI mission traverse concept at the "Relict Glacier" site. Orange: ground track (roving/skiing path); Blue: flight segments; Yellow: local aerial survey loops. (Background image: NASA MRO HiRISE/Kathri & Lee, in prep.

DESIGN MODIFICATION AND SIZING

To successfully meet mission requirements for LILI to explore the surrounding areas of Noctis Labyrinthus, we use atmospheric conditions from the open-source, web-based interactive library *Mars Climate Database v6* to inform various sizing and design efforts [Ref. 15]. NASA Design and Analysis of Rotorcraft (NDARC) tool is utilized to size LILI for forward flight and obtain maximum hover time and ground traverse capability [Ref. 17]. Furthermore, the due to the unique salt-crusted glacier surfaces, LILI's ski-wheel configuration is modified to increase traction.

Atmospheric Condition Characterization

The area surrounding Noctis Labyrinthus is filled with rough, salt-crusted glacier surface terrain that presents a challenging environment for ground traversal. Additionally, canyons and pits with elevations ranging from -0.775 to 1.6 km further complicate mission operations. The three locations of interest in this work are the Noctis Landing site (-0.6 km elevation), Pink Panther thermokarst pit (-0.775 km elevation), and the Relict Glacier (1.6 km elevation). The atmospheric conditions of each location are determined through the Mars Climate Database v6 [Ref. 15]. These parameters are shown in Table 2. Of these entries, the most challenging aerodynamic case is presented by the Relict Glacier location with a density of 0.009 kg/m^3. As such, all sizing efforts in this work use the atmospheric conditions of the Relict Glacier.

Table 2. LILI mission atmospheric conditions surrounding mission site.

	Pink Panther thermokarst pit	The Noctis Landing site	Relict Glacier
Latitude (degrees North)	-8.5	-7.4	-7.4
Longitude (degrees East)	-93	-93	-94.5
Altitude (m)	-750	-600	1600
Temperature (K)	185	183	179
Density (kg/m^3)	0.013	0.014	0.009
Gas constant (J/Mol K)	191	191	191
Specific Heat Ratio (J/K kg)	1.36	1.36	1.36
Dynamic Viscosity (kg/m s)	9.49x10^{-6}	9.41x10^{-6}	9.18x10^{-6}
Pressure (kg/m s^2)	465	523	308

NDARC Sizing – Forward Flight

A low-order sizing was performed using an existing spreadsheet from Johnson et al. (2020) to aid in initial sizing calculations for the NDARC software [Ref. 17]. The results from these initial sizing calculations suggested that four rotors with three blades would be needed to produce sufficient thrust for the payload requirement.

NDARC is an aircraft system analysis tool that can support conceptual design efforts to meet specific requirements [Refs. 18 and 19], and has been used for the conceptual design of various Earth and planetary vehicles, such as a PYTHIA, a quadrotor concept designed for Martian exploration [Ref. 20]. Furthermore, the interactive design environment, An Integrated Design Environment (AIDEN) was used to provide a visual to verify propulsion connections and rotation direction of rotors for LILI, as seen in Fig. 5 [Ref. 21]. The vehicle was sized using a simplified mission profile with a flight distance with a minimum of 3 km per charge. Subsequently, off-mission analyses were performed to determine maximum hover time and ground traverse distance. LILI's ground traverse capabilities are discussed in the following section.

The sizing requirements include a payload of 10 kg, a minimum range of 3 km per charge, and a maximum rotor radius of 1.1 meters. The 10 kg payload requirement is defined by the scientific equipment needed to explore the regions of interest. A nominal value of 3 km flying distance was selected to ensure LILI is capable of leaping across large crevasse fields. Finally, the 1.1-meter maximum rotor radius requirement is derived from size constraints imposed by the need for the vehicle to fit within the aeroshell during deployment.

The NDARC sizing task resulted in a LILI configuration with a gross mass of 33.8 kg capable of flying 3.7 km at a cruise speed of 10.3 m/s (20 knots) following a climb to 1 km for a single battery charge. For hover, the four rotors are at 90 degrees and for ground traverse the rotors are titled at 0 degrees. For forward flight the tilted up to 90 degrees for a given forward flight velocity. For all NDARC forward flight calculations, the rotors were set to 90 degrees. It should be noted that additional modifications to the sizing conditions could be made to potentially increase the cruise range.

A summary of NDARC sizing results for mass, rotor specifications, rotor locations, and maximum travel for ground, hover, and forward flight are provided in Table 3 through Table 6, respectively. A low-order estimation of LILI's battery capability was calculated using the spreadsheet sizing, resulting in a solar cell energy per sol of 1.56 MJ using the solar panel area of 0.62 m^2, though a higher fidelity calculation should be performed. A visualization of LILI's rotor location and rotational direction is shown in Fig. 6 for hover configuration.

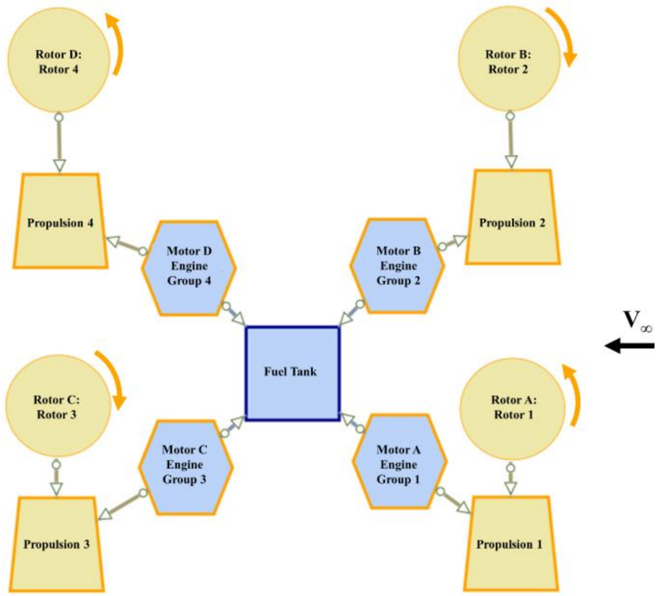

Figure 5. Visual from AIDEN of propulsion connections and rotation direction of rotors.

Table 3. LILI NDARC sizing masses.

Mass specifications (kg)	
Gross mass	33.8
Empty mass	23.8
Structure	8.0
Propulsion	9.2
Systems and Equipment	1.6
Vibration Mitigation Components	0.2
Contingency	4.8
Payload	10.0

Table 4. NDARC LILI sizing rotor specifications. * Initial sizing calculations from low order sizing spreadsheet.

Specifications	
Number of rotors	4*
N_b (per rotor)	3*
Radius (m)	1.1*
Chord (m)	0.17*
Taper	1
Twist (deg)	-10
Disk area (m^2)	3.80*
Solidity	0.15*
V_{tip} (m/s)	180
Disk loading (kg/m^2)	8.78
Solar panel area (m^2)	0.62
Battery capacity (MJ)	2.421
Solar cell energy per sol (MJ)	1.56

Table 5. LILI NDARC sizing for rotor location and rotational direction.

Rotor location and rotational direction				
Rotor	SL (m)	BL (m)	WL (m)	Rotation direction
1	-1.56	1.56	0.55	Counter-clockwise
2	-1.56	-1.56	0.55	Clockwise
3	1.56	1.56	0.55	Clockwise
4	1.56	-1.56	0.55	Counter-clockwise

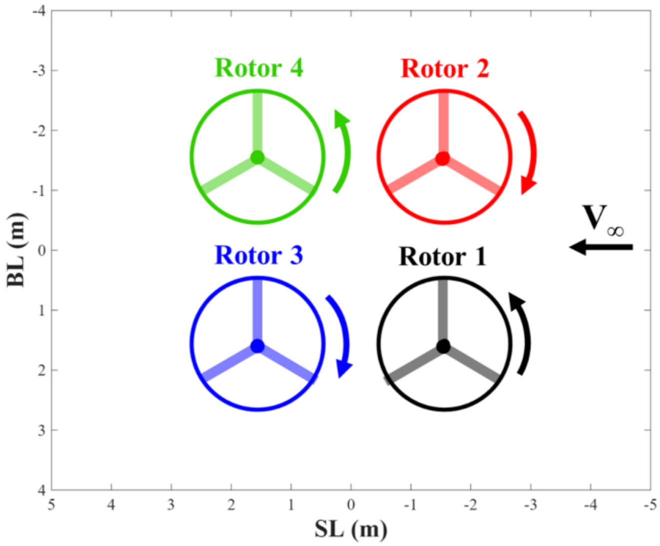

Figure 6. LILI rotor location and rotational direction visualization in hover configuration.

Table 6. LILI ground and air maximum travel distance, velocity, and time.

Ground and Air Travel per charge	
Ground traverse	
Distance (km)	13.8
Velocity (m/s)	1.0
Time (min)	224
Hover	
Distance (km)	N/A
Velocity (m/s)	0.0
Time (min)	9
Forward Flight	
Distance (km)	3.7
Velocity (m/s)	10.3
Time (min)	6

Driving Range Estimation

NDARC was used to estimate the maximum driving range for the sized configuration by first calculated required thrust needed. The required thrust force for ground traversal was calculated by estimating the following forces: x-force, drag (which we find to be negligible), and friction. The drag force is estimated to be negligible due to the low forward velocity. A visual of forces acting on LILI for a single front ski/wheel is shown Fig. 7, and a table of values is shown in Table 7. For this sizing study, a ground traverse speed of 1.0 m/s (2 knots) and a conservative ground slope of 20 degrees were used to account for the uneven terrain, with an estimated tire friction coefficient of 0.055. Values of slope angle and tire coefficient should be further refined for future sizing efforts and calculations. The power and energy flow required to achieve the thrust force necessary for ground traversal were computed in NDARC. From this, the total distance LILI could travel by ground was calculated to be 13.8 km for a velocity of 1 m/s.

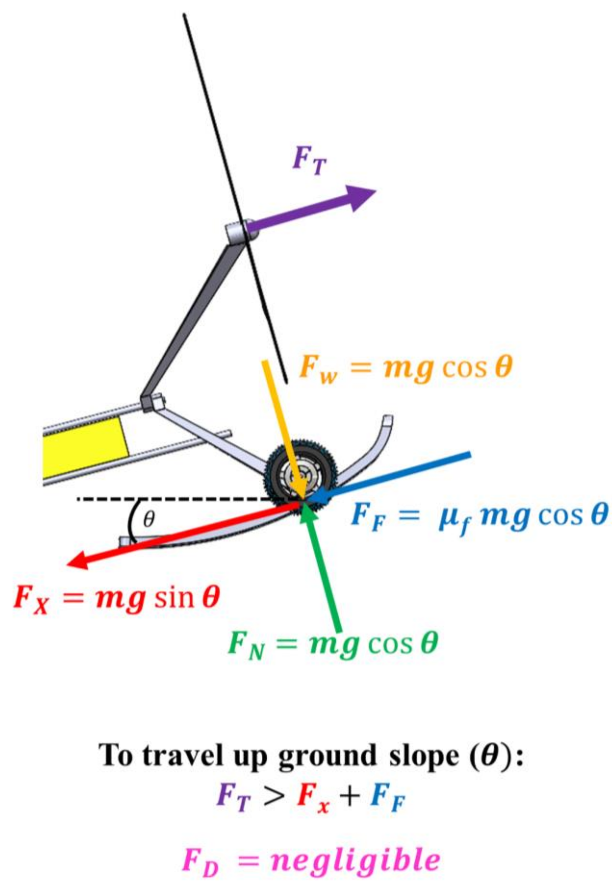

Figure 7. Identified forces acting on LILI driving up an incline for a single front ski/wheel.

Table 7. Driving range estimated calculations for LILI at the Relict Glacier.

Driving Range Estimation	
Mass (kg)	33.8
Gravity (m/s^2)	3.7
Friction coefficient	0.055
Ground slope (deg)	20
Ground speed (m/s)	1.0
F_x (N) (Total)	42.89
F_F (N) (Total)	6.48
F_D (N) (Total)	0.000
F_T (N) (Total)	49.37
F_T (N) (per rotor)	12.34
C_T/sigma	0.0002
Power required (kW)	0.17
Energy flow (kW)	0.18
Battery capacity (mJ)	2.42
Time (min)	224
Distance (km)	13.8

Design Modifications

Due to the harsh terrain of the mission location and payload requirements, design modifications from the vehicle proposed in Reference 7 were considered to meet mission requirements and scientific goals. Design modifications include reconfiguration of the frame to account for four rotors, two skis, and four wheels. Additionally, an improved wheel design and storage location of scientific instrumentation are presented. All structural modifications are made considering the 8 kg structural mass constraint determined from sizing results shown in Table 3. A 3D rendering of the sized LILI concept vehicle is shown in Fig. 8 a) hover and b) ground configuration.

Improvements to LILI's wheels are implemented to account for the challenging and variable terrain in the Noctis Volcano region. Building upon the wheel design from the 2020 Mars Perseverance rover [Ref. 16]. A proposed design of the wheels is shown in Fig. 9. The ski + wheel configuration was only implemented in the front of the vehicle to reduce weight and ensure that the rear would not get caught on boulders.

In our proposed vehicle configuration, the scientific instrumentation and equipment are placed in the center of the vehicle connected by the front and back nacelle beams to allow scientific studies to be performed directly under the storage box without intrusion from the ski-wheel structure. Furthermore, the location of the 10 kg science payload is determined such that the center of gravity of the vehicle remains close to the center of the vehicle chassis. Currently, the top area of the storage box of scientific instrumentation serves as the location for the solar panel with an area of 0.62 m^2.

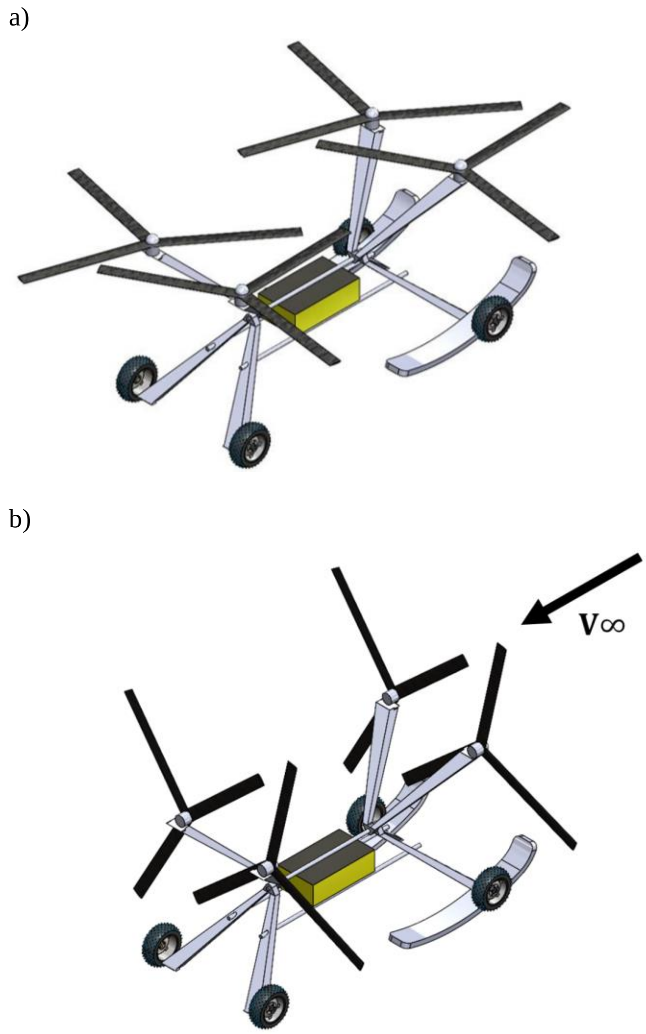

Figure 8. LILI concept vehicle in a) hover and b) ground configuration.

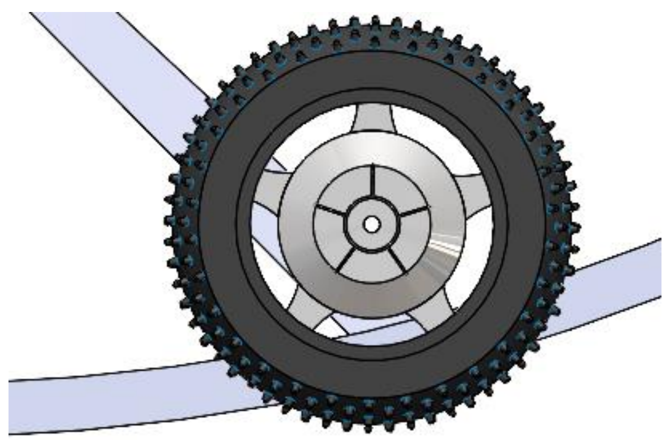

Figure 9. Modified LILI ski-ice spike wheel using 2020 Mars Perseverance rover wheel as baseline.

FUTURE WORK

This paper presents a preliminary design for a hybrid aerial/ground vehicle, tailored to a mission profile that navigates to specific points of interest in the Noctis Labyrinthus region on Mars. There are several components not addressed in this work that would be important to further investigate feasibility of this mission. Two main avenues of future work considered are guidance, navigation, and control of the vehicle, and small-scale prototype testing.

Guidance, Navigation, and Control

While developing the Mars helicopter technology demonstrator (Ingenuity), Balaram et al. identified the many challenges of designing a robust control system for a Mars rotorcraft, with some of the most critical challenges being (1) the drastic difference in atmosphere and gravity as compared to Earth, (2) limited prior information on how these differences affect flight dynamics in the Mars environment, and (3) inability to fully replicate the operating environment on Earth [Ref. 22]. After the many successful flights of Ingenuity, these challenges and testing capabilities are better understood. However, there is still much to learn [Refs. 23 and 24].

The LILI mission presents several interesting problems for developing an effective control strategy. With respect to high-level decision making, the mission profile spans a long distance and duration with many terrain variations, so traversability decisions will need to be made in near real-time with onboard vehicle sensor information. While Mars geodetic coordinates of each site of interest can be pre-mapped prior to the mission, traversal mode (ground or flight) may need to be selected by the vehicle without human consultation. Coarse decisions can be made a priori with knowledge of certain regions along the mission profile, but regions with unpredictable terrain or weather conditions will require more autonomous decision making by the vehicle. Decision algorithms and sensor requirements will be further developed in future work using a small-scale prototype of the vehicle, detailed later in this section.

In addition to high-level decision making, the LILI vehicle itself is a novel design requiring low-level controllability assessments. Using the NDARC flight vehicle model, stability characteristics can be assessed with FlightCODE (formerly known as SIMPLI-FLYD [Ref. 25]), to produce linearized dynamic models of the vehicle. These models will then be used to develop the flight control laws. A similar approach may be used for ground traversal control, and transition between the two modes is intended to be largely binary (i.e. vehicle will transition modes from a static condition).

Figure 10 shows a notional block diagram of the control strategy. Desired locations are sent from the Earth-based scientists, directing the vehicle to areas of scientific interest. Once LILI receives a destination, the vehicle will determine the optimal path to reach that destination, considering current vehicle state, power available, terrain, and atmospheric conditions. This guidance computer will determine when LILI can traverse along the ground and when flight is required. Those decisions will be sent to the control laws to command the vehicle. The onboard sensor package and state estimator will gather data and feed it back to the guidance computer for continuous path optimization and to the control laws for aircraft stability and control.

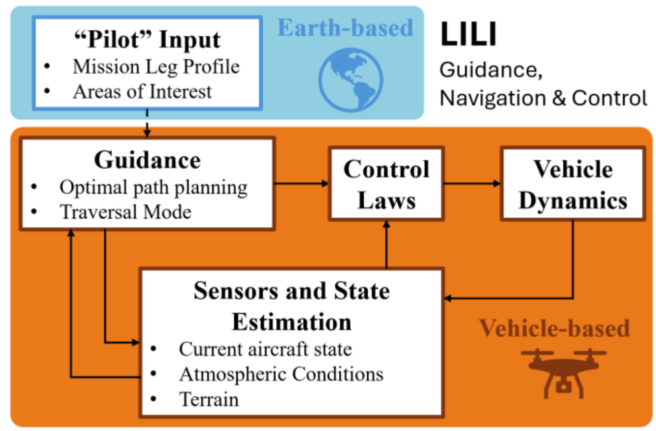

Figure 10. Notional block diagram of LILI control strategy.

Small Scale Prototype Development

To further investigate feasibility of the LILI hybrid aerial/ground vehicle, we have initiated work to build a small-scale simplified prototype of the proposed vehicle. The stability of the vehicle requires controllability in all axes: roll, pitch, heave, and yaw. To simplify the design of the small-scale prototype, a quadrotor platform is used with variable RPM control. The quadrotor is further modified with skis and a tilting mechanism that allows the full body of the quadrotor to tilt, similar to the design of the full vehicle shown in Fig. 8. Figure 11 illustrates the LILI prototype in both a) ground traversal and b) hover configuration.

The quadrotor used is a DJI F330 frame with 8-inch propellers, and a Pixracer Pro flight controller. The skis are custom-designed and 3D printed.

Air and ground testing of the small-scale prototype is left to future work and will be conducted in NASA Ames Research Center's UAV Autonomy Research Complex, featured in Ref. 26. To simulate surfaces similar to those encountered on Mars, the LILI prototype will navigate over a tarp lined with salt when in a ground vehicle configuration. Depictions of the testing facility are shown in Figure 12 a) and b).

a) b)

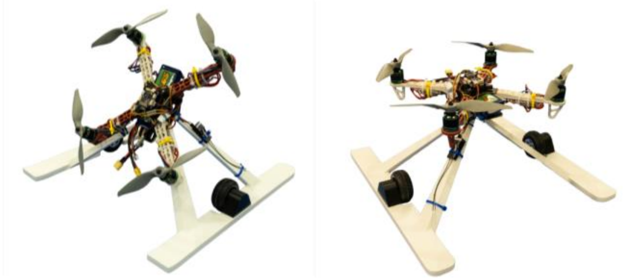

Figure 11. LILI concept protype vehicle in a) ground and b) hover configuration.

a) b)

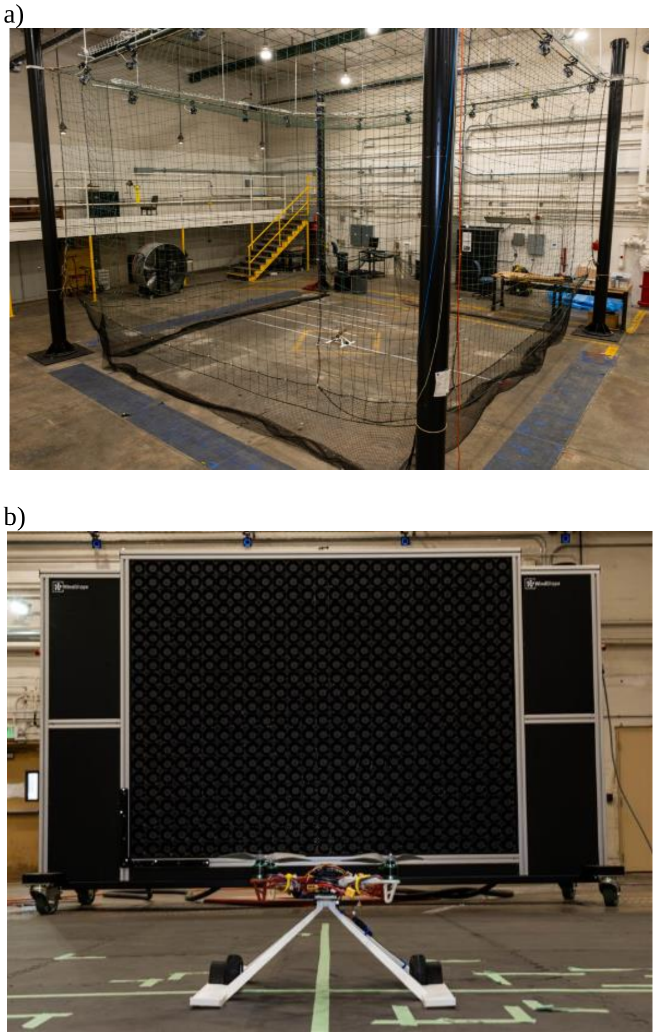

Figure 12. NASA Ames Research Center's motion capture and UAV Autonomy Research Complex with LILI prototype vehicle in the a) netted cage and b) in front of the WindShape fan array.

CONCLUDING REMARKS

With an exciting new salt and potentially ice-rich target in Noctis Labyrinthus, the use of a LILI vehicle is sized and analyzed to explore this region of Mars. Initial efforts have identified areas of interest surrounding Noctis Labyrinthus with a notional traverse concept path. NDARC was used to size LILI for the nominal mission while considering all constraints such as required distance, rotor radius, and payload. Structural design modifications from the earlier LILI conceptual design were defined for ground exploration using a wheel with ice spikes to better traverse the rough, salt-crusted glacier terrain. An initial look into guidance, navigation, and control indicates the need for autonomous decision making and path planning. To advance technological capabilities and in-house expertise, efforts for a LILI prototype are ongoing.

Further sizing, modeling, and testing should be performed to develop the hybrid aerial/ground vehicle for exploration on Mars. In summary, we list avenues of potential future work:

- Perform sizing optimization within NDARC to increase flight and driving range with possible increased gross mass while varying rotor geometry (radius, number of blades, etc.).
- Improved structural design to include modifications to ski-wheel configuration and perform structural analysis.
- Perform solar panel sizing study and calculate required time to charge.
- Further develop prototype to enable flight and ground testing at NASA Ames Research Center's UAV Autonomy Research Complex.
- Outdoor ground traversal testing of a prototype vehicle.
- Research optimal power management and aerial/ground configuration control strategy.

These efforts and more should be performed to further understand the feasibility of a LILI vehicle to explore Noctis Labyrinthus, the Maze of the Night (see Fig. 13 of LILI concept protype vehicle depicted in forward flight at Noctis Labyrinthus).

Figure 13. LILI concept protype vehicle simulated in forward flight in the Noctis Labyrinthus region of Mars.

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APPENDIX:

PRELIMINARY AERODYNAMIC STUDIES

Using Rotor Unstructured Navier-Stokes (RotUNS), several preliminary aerodynamic studies were performed. RotUNS is one of many flow solvers that operates within the RotCFD Integrated Design Environment (IDE), which also includes a geometry module, a semi-automated grid generation module, a rotor module, and a flow visualization and analysis module [Ref. 27 and 28]. A preliminary aerodynamic wake interaction study was performed for LILI in hover and forward flight with skis and with wheels separately. The use of a "Skycrane" to lower the rovers onto the surface is introduced for Entry, Descent, and Landing (EDL) efforts. An aerodynamic qualitative study was performed on the Skycrane jet plume direction.

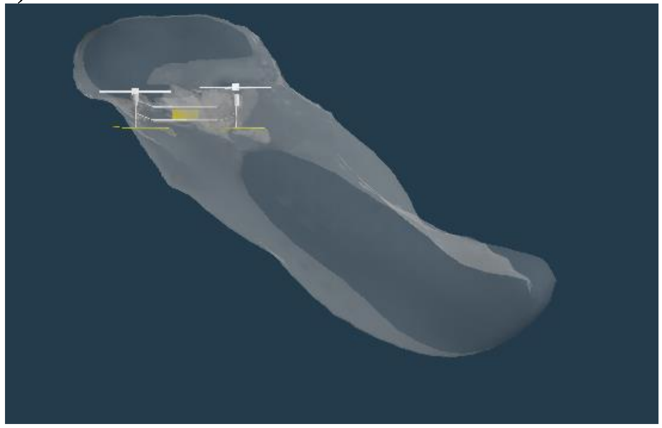
Aerodynamic Wake Interaction Studies

An ablation study on qualitative aerodynamics was performed using RotCFD to understand the wake distortion of the NDARC sized LILI design with skis and wheels separately in hover and forward flight. For all forward flight conditions presented, the rotors are placed at 90 degrees to capture worst case scenario of wake interaction with skis and wheels.

A qualitative wake visualization study was performed for a forward flight velocity of 10 m/s. This study focused on the contributions from the skis and wheels individually, each shown in Fig. 14 a) and b), respectively. Between the two configurations, the addition of the wheels reveals larger regions of wake distortion due to the larger frontal flat plate area compared to the skis.

Similarly, a qualitative study was performed in hover for a wake visualization with skis and wheels and is shown in Fig. 15 a) and b), respectively. In comparison between the ski and wheel configuration, the addition of the skis reveals larger regions of wake distortion due to larger top surface area of the skis compared to the wheels. In conclusion, the design of a ski + wheel and wheel configuration must be considered in future aerodynamic analysis.

a)



b)

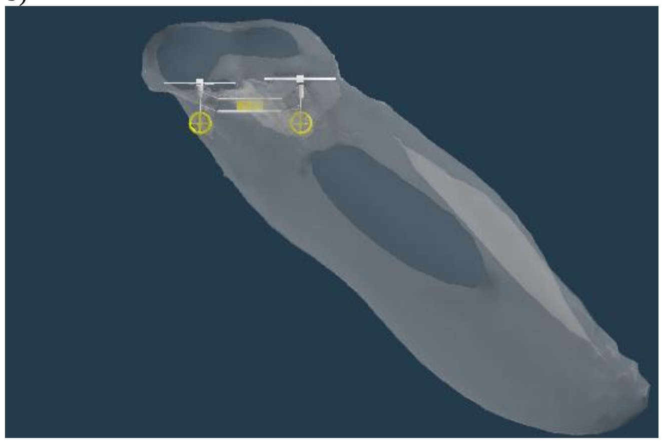
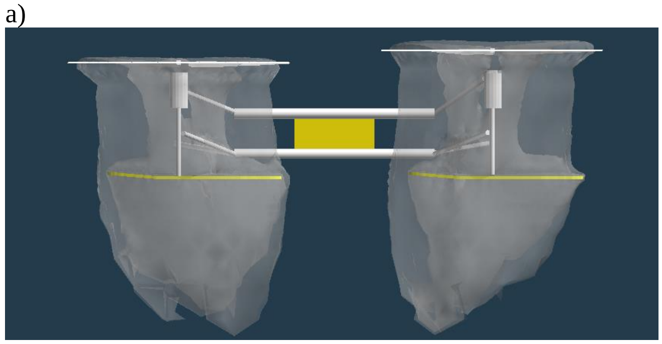


Figure 14. LILI in forward flight at 10 m/s with wake visualization a) with skis and b) wheels (side view).

a)



b)

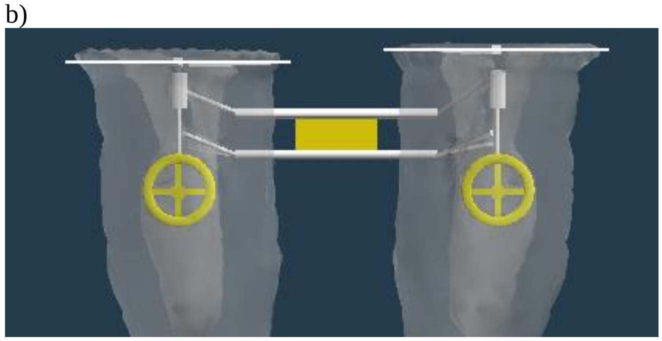


Figure 15. LILI in hover with wake visualization differential a) with skis and b) wheels (isometric view).

Skycrane jet plume studies

In addition to development of the vehicle itself, the LILI mission must consider methods for EDL. Most recent Mars rover missions, Curiosity and Perseverance, used a Skycrane to lower the rovers onto the surface [Ref. 29]. The Skycrane approach involves an aeroshell that descends into the Mars atmosphere and decelerates by a parachute. A propulsion system onboard the aeroshell then activates to further decelerate the aeroshell until the rover can be lowered by a series of cables [Ref. 30].

To evaluate the feasibility of this EDL approach with the LILI vehicle, a qualitative study was performed on the Skycrane jet plume direction. The resulting velocity magnitude iso-surface is shown in Fig. 16 a) and b) for a jet plume cant angle of 15 and 30 degrees, respectively. Qualitative results reveal a jet plume cant angle of 30 degrees does not impinge on LILI at the current tether length of 15.4 meters. This low-order analysis allows for a more complete mission design that is inclusive of how LILI will be deployed on to the surface of Mars.

a) b)

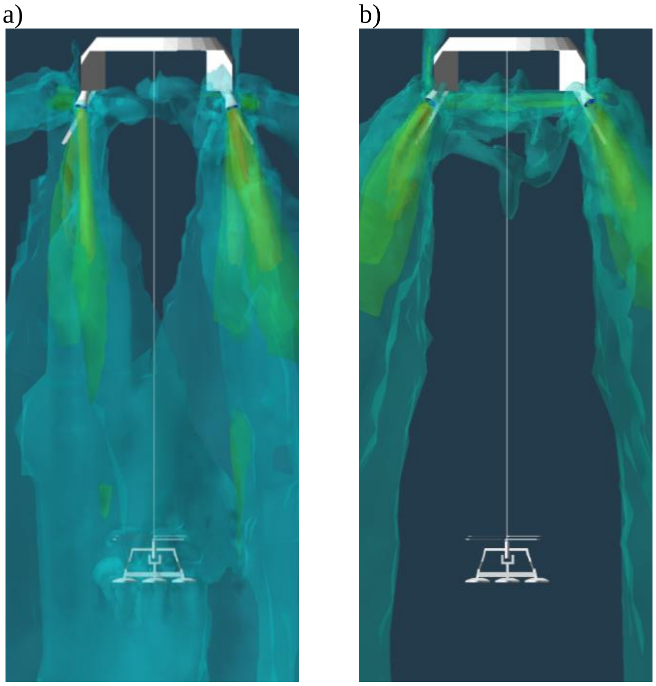


Figure 16. LILI on tether attached to skycrane-like transporter with a cant angle thruster of a) 15 and b) 30 degrees.

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