VERTICAL TAKEOFF AND LANDING UAVS FOR EXPLORATION OF RECURRING HYDROLOGICAL EVENTS.

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Introduction: We describe a payload/investigation that is responsive to program objectives of the Science Mission Directorate (SMD), the Human Exploration Operations Mission Directorate (HEOMD), and Office of Chief Technologist (OCT), is achievable in the near term (2018), and may be accommodated as a secondary payload on a mission in which the primary platform is a large orbiter, or lander "mothership". The payload explores recently discovered dynamic surface features that are indicative of the presence of flowing surface water. The exploration platform is an all-electric Vertical Take Off and Landing (VTOL) Unpiloted Air Vehicle (UAV) capable of semi-autonomous flight, including multiple landings and takeoffs. The ability to hover in proximity to the surface while simultaneously measuring surface slope and roughness, for minutes at a time before attempting a landing, radically increases accuracy and reduces risk of autonomous landings. The ability to fly at speeds ≈ 10 m/s above rough, high-angle slopes while carrying science instruments allows efficient exploration of portions of the Mars surface not accessible by the current generation surface rovers.

Rationale: Mars is not a dead planet; there exist recently discovered transient surface flow processes occurring at discrete locations and times whose understanding has importance for the global story of water on Mars. The most compelling evidence for present-day water activity on Mars are the Recurring Slope Lineae (RSL)**[1]**. The RSL are narrow (0.5-5 meter) relatively dark markings that emanate from bedrock outcrops and extend hundreds of meters downslope, often in association with small channels. RSL are located on mid-latitude, steep (25°-40°), mostly equator-facing slopes and are active during the warmest times of the year. Repeat imaging by HiRISE (High Resolution Imaging Science Experiment) shows their seasonal formation, growth and fading. It is thought that RSL form from melting of shallow ice which results in the flow of a briny water-based liquid **[1]**. Therefore, RSL are a high priority for both SMD and HEOMD in situ investigation given their likely association with both present-day liquid water flows on the Martian surface and water ice in the near subsurface.

Within SMD, the guiding philosophy of the Mars Exploration Program (MEP) has been to "Follow the Water" in order to understand recent climate and geology, and to assess the potential for habitability and life on Mars. For HEOMD, water may be a valuable resource for In Situ Resource Utilization (ISRU) to enable long duration human exploration. The presence of water is also important for planetary protection and crew safety. Liquid water habitats have the highest potential for harboring life on Mars; thus the search for extant life on Mars focuses on regions where liquid water may exist to support Martian biota. The possibility of indigenous Martian life must be addressed prior to sending humans to Mars, to understand potential biologic threats to the crew.

While representing potentially high payoff for SMD and HEOMD, the RSL sites also represent high technical challenge for exploration. A site often mentioned as a good candidate for RSL exploration is Horowitz crater, located at 32°S, 140.8°E at an elevation of -0.5 km (MOLA). Horowitz crater is approximately 15 km in diameter and possesses a large flat floor suitable for a non-challenging landing, that surrounds a central peak containing the RSL features. The RSL features of Horowitz crater are superimposed on jumbled surfaces of high average roughness.

Payload Description: A candidate payload to investigate the RSL features centers around the ability to definitively determine whether or not the dark RSL streaks are formed by liquid water and whether or not near-surface ice at the heads of the streaks is a source of the water. To achieve these objectives, a small prospecting payload could consist of a near-infrared (NIR) point spectrometer to measure the RSL streaks for water content, and a neutron spectrometer (NS) to measure hydrogen (ice) abundance in the near subsurface at the heads of the RSL. An NIR spectrometer of the type flown on NASA's LCROSS (Lunar Crater Observation and Sensing Satellite) mission **[2]**, spanning the wavelength band 1.20-2.45 microns is ideally suited for the detection of water and successfully detected water on LCROSS. This NIR instrument has a mass of ~3 kg and requires 5 W of power. An NS (currently at TRL 6) with a mass of 480 g, consumes 1.8 W of power. When the NS detector is near the surface it is sensitive to H down to ~1 meter depth **[3]**. Another critical instrument would be a high-resolution color (stereo) imager sufficient to measure grain-size and textural changes of the RSL and surrounding surface units. Such changes are typically seen in water transported material with increasing distance from the source region. In addition, subtle color changes associated with these units may indicate compositional changes (such as the presence of salts) Comparing data from the NIR spectrometer and NS, together with the information from the high-resolution imager provides a payload capable of testing the water origin of the RSLs.

Concept of Operations--Because the RSL are dynamic features with predictable time constants located at some distance from safe landing sites, exploring them will require a mobility platform for the science instruments capable of both moving from a safe initial landing site to the vicinity of the RSL features (≈ 5 km) over relatively smooth terrain, and then exploring areas of interest within the steep slopes and rough surface of the RSL field, in reaction to observed changes, and with ≈ 1 m accuracy. Moreover, in order to avoid the cost and risk of a multi-Mars-year mission, the exploration must be achieved within approximately a 90 day period. This set of mobility platform attributes does not lie comfortably within the performance envelope demonstrated by wheeled surface rovers, but does lie within the envelope of heavier-than-air UAVs—specifically rotary wing VTOL aircraft (helicopters, tilt-rotors, etc.)

Operationally, a Mars VTOL UAV can be deployed from either a landed station, or mid-air, from a descending atmospheric entry vehicle (EV). In the later case, the folded UAV will be dropped from the EV backshell, while the backshell is suspended on its parachute harness, ≈ 0.5 km above ground level. The UAV will autonomously power up its main rotor, fly away from the backshell (to avoid recontact) and begin a controllable, slow descent to the surface. During the first descent, the UAV will execute a preprogrammed spiral flight pattern at constant altitude to image all potential landing sites within an ≈ 100 m radius circle. Using onboard pattern recognition software, it will select the safest (smoothest) site within the search area and perform an autonomous landing. It will recharge its batteries and transmit engineering data and descent images to a Mars relay orbiter. After recharging, the UAV will be commanded from Earth to reconnoiter its next landing site, located on a path in the direction of the RSL features, and then return to its first landing site. On the following flight, it will land at a site reconnoitered on the previous flight. This process allows the UAV to always land at a site that has been determined to be low risk by a previous flight, and will be repeated until a safe landing site is located close to the RSL field (the "Forward Landing Zone", or FLZ). Data collection overflights of the RSL features will depart from and return to the FLZ.

Technical Readiness: During an approximate five-year period from 1998 to 2003, NASA's SMD and ARMD made tens of M$ investments in increasing the Technology Readiness Level (TRL) of fixed wing heavier-than-air Mars UAVs, with the result that in 2003 a Mars airplane mission (ARES) was determined to be selectable for flight in the Mars Scout competition (narrowly losing out to the Phoenix lander mission). Earth-based, high altitude flight experiments funded by SMD's Mars Technology Program and conducted by Lemke, et. al. in 2001-2002 proved that airfoil design tools developed for terrestrial air vehicles are extensible to the Mars environment with high accuracy [**4**]. Both wings and lightly loaded propellers were designed and demonstrated in flight at ≈ 30 km altitudes and performed to within ≈ 5% of predictions. Young, et. al., designed, constructed, and tested a 2.4 m diameter rotor in the NASA-Ames Mars Hover Chamber in 2002 that demonstrated the ability of a free-flying helicopter UAV of ≈ 10 kg mass to generate net positive lift at Mars atmospheric density and gravity levels [**5**], Fig. 1.

Figure 1: Test of conceptual Mars VTOL UAV rotor in NASA-Ames Mars Hover Chamber. Rotor is sized for ≈ 10 kg UAV, is scalable to 50 kg UAV.

Foch, et. al., in Navy efforts parallel to NASA work, designed, tested and certified for US Navy fleet use, technology for helicopter UAVs to navigate with machine vision, autonomously take-off, hover, transition to and from forward flight, and to land, as well as the technology for mid-air deployment of folded airframe flight vehicles [**6**]. Collectively, this set of accomplishments has brought the ability to design a small, electric powered Mars helicopter UAV to TRL7. Moreover, such a UAV could be tested at the system level prior to deployment at Mars. Overall, the technical risk of such a UAV would be small, by the time of deployment.

We calculate that it is possible to design an electric Mars helicopter UAV with a gross mass of 50 kg carrying a payload of approximately 5 kg. For power, it would utilize secondary lithium-polymer batteries recharged by GaInP/InGaAs/Ge solar arrays (25% to 29.5% efficiency, if optimized for Mars'redder spectrum) when not in flight. With a battery mass fraction of 0.33, this UAV would be capable of a flight endurance of 20 minutes between recharge cycles, at a forward flight speed of 10 m/s, for a no-wind range of 12.0 km. This calculation is supported by an American Helicopter Society design competition of 2000 in which a Mars helicopter with similar performance parameters, was designed by the winning team from the University of Maryland.

Given the aggregate technology investments to date, the power and propulsion, the GN&C, and the aerodynamics requirements of a Mars UAV helicopter are well understood. The primary technical challenge for such a UAV is in achieving a low enough disc loading (≈ 4 N/m^2) to allow the transport of a useful payload. Key to achieving this performance parameter is the ability to construct lightweight rotor blades in the correct size range. The technical risk of a Mars VTOL UAV could be reduced substantially by the early infusion of targeted technology investment to demonstrate prototype blade manufacturing. Assuming a nominal 5-year flight hardware development schedule, a technology investment beginning in FY2013 would allow the rotor system to be at TRL6 or higher by PDR, for a 2018 launch. The 2018 launch opportunity is particularly favorable for RSL exploration since it allows arrival of the spacecraft during Martian mid-summer in the Southern hemisphere ($L_s = 320$) when the RSL phenomena are appearing.

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