EXPLORING MARS WITH MICRO-UAV SQUADRONS AND HIGH DATA RATE COMMUNICATIONS.

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Introduction: We describe a new capability and architecture to enhance mission operations at, and scientific return from, Mars. Small (≤ 10 kg) multi-rotor aircraft, often described as micro-UAVs or simply UAVs, offer an effective and unique system capability for martian surface exploration. Extensive regions of Mars may be investigated from a vantage point that ranges from the martian surface up to an altitude of ~1 km. Primary mission data are linked through a base station at the core of each airbag-deployed EDL (entry, descent, and landing) package [1]. Solar cells aboard each UAV charge the UAV batteries sufficiently to support one flight every four martian sols. Flight durations of up to ~20 minutes permit a host of mission profiles ranging from hovering over a single location to long-range flights to a distance of ≤12 km while returning to the EDL base on a single battery charge. Using an onboard satellite communication system UAVs may explore distal regions without returning to base. (Fig 1.)

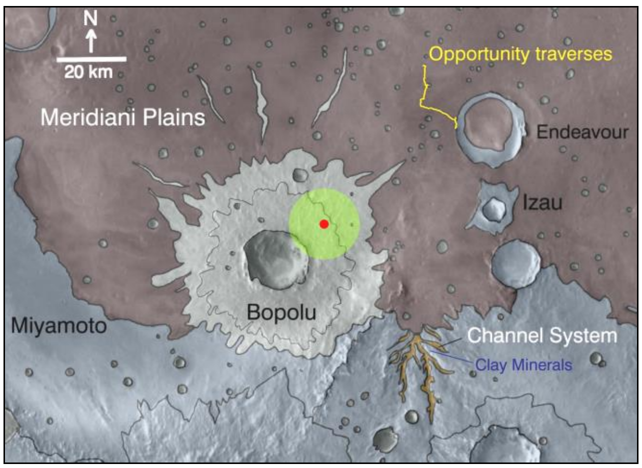

Fig 1. The red dot represents the zone of unrestricted UAV high-speed communications with the EDL base station. The green area represents the zone that may be accessed during a single sortie that returns to the EDL base. Two sequential sorties may access the present-day location of the MER rover. The entire mapped region may be accessed within five sequential sorties. *Image: NASA/JPL-Caltech/JHU-APL/WUSTL.*

UAVs may assist mobile rover and fixed lander operations by collecting science observations at low-altitudes and producing 3D maps in spectral ranges from UV to thermal wavelengths [2, 3]. On-board sensors will include the capability to pinpoint the location of methane sources that may be present in abundance according to recent measurements by the SAM instrument aboard the NASA/JPL Curiosity rover [4]. UAVs may also support future human-explorer surface activities by providing context images and surface samples for on-site analysis. Over a period of several weeks or months UAVs may also conduct distal reconnaissance missions that are designed to explore a ground track that extends up to several hundred km from its base station by interconnecting a sequence of individual sorties before returning to base (Fig 1.).

System configuration: At four landing sites, EDL systems deploy a squadron of six micro-UAVs for a total global deployment of 24 UAVs. Each UAV has a launch mass that is ≤10 kg and a volume that is ≤0.1 m^3. The low mass and volume of the primary payload permits a substantial mass and volume budget for each EDL package that is allocated to a powerful phased-array data relay base station. The radio system provides each landing site with a high data rate communications link with the Earth and with Mars-orbiting spacecraft. The EDL base station radio antenna is ~2 meters in diameter and may be steered electronically without moving parts. Up to 10 m^2 of solar collection area is deployed to power the communications system. UAV rotor downwash is used to remove dust from the base station solar cells. Dust that collects on the UAVs is removed during UAV flight.

Because of the low mass and modest volume of each EDL package, a single launch from Earth (Atlas V, Delta IV, or Ariane 5) inserts all four EDL packages to the surface of Mars in one launch, plus a laser communications satellite into a Mars orbit. The addition of the four martian ground-based radio communication links doubles the maximum Mars-to-Earth radio data rate among active missions at Mars from ~6 to ~12 Mbs [5] and produces the backbone of a truly global martian data relay and deep space communication system. The laser communications satellite occupies a 400 × 41,500 km 32-hr orbit at an inclination that is designed to precess with a phase angle that remains oriented with the Earth. The 32-hr orbit lingers over the equator of Mars for an entire martian sol and thereby ensures daily global data relay coverage. All science missions on Mars may access the high speed laser link to relay science data to Earth at a faster data rate. Depending on the speed of the local radio transmission data within the network, data from any landing site or from any orbital mission at Mars may be transmitted to Earth via laser link at up to 120 Mbs, which is ~20X faster than the highest data rates from Mars to Earth in the present day [5].

Engineering challenges:

Rotor efficiency. Compared to the Earth at sea level, the surface atmospheric pressure of Mars is approximately 1/120th with a molecular density that is ~1/60th. Empirical studies in our lab indicate that rotors that are optimized for vertical flight convert power to lift with an efficiency of ~80%. When we test a standard Earth-optimized rotor under martian conditions, the efficiency drops to ~14% (Fig. 2). This initially suggests that ~6X greater power is required to achieve comparable flight at Mars (80% ÷ 14%). However, the gravity of Mars is ~1/3 of the Earth, and a comparable lifting capacity may be achieved with a rotor that is optimized for Mars with a power-to-lift efficiency of ~27% (80% ÷ 3). Because the mass of the UAV is not reduced (only the weight is reduced), this requires an added efficiency margin to offer increased flight stability and maneuverability. Consequently, the target efficiency of a martian UAV rotor should be ≥30%.

Demonstrating the likelihood of the required efficiency, the Jet Prolusion Laboratory produced a viable helicopter proposal for Mars 2020 [6] and the NASA Helios solar powered wing flew with rotor propulsion to an Earth altitude of >96,000 feet in 2003 [7]. This suggests that a sufficiently optimized UAV rotor at Mars is highly probable. Further, if the efficiency of a martian rotor design is $> 30\%$, UAVs at Mars will be capable of longer flights and/or heavier payloads than a comparable multi-rotor vehicle on Earth.

Fig. 2. An 8-inch carbon fiber UAV rotor that is optimized for sea level flight on the Earth (80% power-to-lift efficiency) produces lift with an efficiency of only ~14% at an air pressure that is typical of the surface of Mars (7 mbars). An optimized rotor efficiency of ~30%, plus the lower gravity of Mars, would permit Earth-equivalent flight performance at Mars.

Navigation without GPS or magnetic reference. The flight of UAVs on Earth is typically referenced to geospatial data provided by the GPS system plus angular information from the magnetic field of the Earth [8]. There is no GPS system at Mars, nor is there a global magnetic reference. Consequently, UAVs will navigate at Mars through a combination of available references including the known sky position of the Sun, and radio or optical beacons that are produced by the EDL base station or non-flying UAVs that have known landing site locations. Also, as each UAV flies, a ground-facing camera system, operating in many ways like a star-tracking camera [9] will produce a basic on-board 3D terrain map that is rooted to clearly observable ground features. Navigation will be accomplished by comparing the camera data to previously observed features. Because the exploration of new terrain is an extension of previously observed terrain, the UAV remains constantly within the bounds of its own map. Map data may also be shared among the UAVs of a local squadron and overlaid onto a wider-field map that is produced from orbital data. Using the orbital base map, each UAV can anticipate navigational reference points prior to arriving at a new exploration zone.

Distal RF links. Sorties that travel beyond the near proximity of the EDL base station may lose contact with the EDL base station due to the excessive transmission distance or the intervention of terrain elevations that block line-of-sight communications. During distal exploration flights, limited data may be uplinked directly to Earth that is sufficient to observe the general health status of the sortie. When Mars-orbiting satellites are available, uplinked data may be relayed to Earth at a faster rate. Once a UAV returns to the proximity of its EDL base station, high-volume science data that is collected during the sortie may be relayed to Earth.

Methane sensing. UAV rotor downwash stirs and mixes the ambient air, and therefore a gas sensor must either sample from a boom that extends beyond the rotor blades or measure with a stand-off laser-based system [10]. Most gas-sensing instruments that are suitable for UAVs in terms of mass and power consumption provide methane measurements of $\geq$ 1ppm [10]. However an optimized measurement level of $\leq$7 bpm will be required to detect methane concentrations that are consistent with the recent measurements of the Curiosity rover's SAM instrument [4]. If a UAV locates a methane source, it will land nearby and measure production rates over a period of time. Ideally, isotopic species of methane and other gases will be identified that place constraints on the processes that produce the gasses. Alternately, a UAV may direct a rover toward a suspected methane source site or return a gas sample to a rover or lander for analysis.

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Summary: We describe a single-launch exploration mission of four low-mass EDL packages that deliver a total of 24 micro-UAVs to the surface of Mars. The low mass of the UAV payload permits a parallel mission where the landed EDL packages provide the backbone of a global communications infrastructure in concert with a laser link satellite that is capable of boosting the Mars-to-Earth data rate of all active Mars missions by a factor of ~20X. Key engineering challenges are overcome that address rotor performance, navigation, communications, thermal issues, and methane sensing.

References: **[1]** http://mars.nasa.gov/mer/mission/tl_entry1.html. **[2]** Nex and Remondino, (2014) *App Geomatics, 6,* 1-15. **[3]** Mitchell et al., (2012) *4th Workshop on Hyperspectral Image and Signal Processing.* **[4]** http://tinyurl.com/nyyncjn. **[5]** http://tinyurl.com/qjefjkl. **[6]** http://tinyurl.com/pzhszee. **[7]** http://tinyurl.com/mhvptxa. **[8]** Barczyk and Lynch, (2012*) IEEE Transactions on Aerospace and Electronic Systems, 43*, 2947-2960. **[9]** Barfoot et al., (2012) *IEEE Aerospace Conference.* **[10]** http://tinyurl.com/kf4a5yf.