**HOPPER/ENTOMOPTER TANDEM SYSTEM FOR SURFACE AND SUBSURFACE EXPLORATION OF MARS.** T. R. Gemmer[1], S. Aggarwal[2], A. S. Bakunov[3], and T. N. Jordan[4] [1]N.C. State University trgemmer@ncsu.edu, [2] N.C. State University saggarw2@ncsu.edu, [3] N.C. State University asbakuno@ncsu.edu, [4] N.C. State University tnjorda2@ncsu.edu

**Introduction:** Conventional systems utilized in the exploration of the Martian surface are severely limited by their mobility. During its nine year mission, the Opportunity rover covered only 32km of ground. Proposed aerial platforms like the ARES were expected to exceed 500km range but lacked endurance, with flight time of only 40-60 minutes. In both cases, the amount and variety of scientific data collected is limited by small area of coverage or short mission duration.

A hopper-type rover combines the advantages of both the ground based exploration vehicles as well as aerial platforms. The primary mode of locomotion for a hopper system is a series of ballistic trajectory jumps. Jumping takes advantage of low gravity and density of the Martian environment. The vehicle achieves superior mobility due to its ability to jump over obstacles and difficult terrain. Unlike an aerial vehicle, the hopper does not need to stay in flight for the entire duration of the mission. In addition, the hopper's operation is not restricted by altitude because it does not need to generate lift in order to jump. The hopper will be complimented with an entomopter scout which will be able to explore nearby terrain and find suitable landing locations for the hopper. Entomopters are capable of operating in low Reynolds number regimes, and are thus ideal for flying in the Martian atmosphere.

**Mission Goals:** The hopper mission will be focused on seeking habitable environments, and will directly correspond to MEPAG Goals 1 and 4. The vehicle will look for evidence of past and present indigenous life, as well as assess the Martian environment for feasibility future human exploration. This will include looking for bioessential elements (C,H,N,O,P,S) and evidence of water. Since liquid water is not stable on the surface of Mars, subsurface environments are the best candidate for investigating these goals. Several volcanic lava tubes have been observed on the northern slope of Arsia Mons at 5-12km altitude above datum. These locations are to be explored by the hopper system. Lava tubes are an ideal candidate for finding habitable environments due to their shielding from radiation, micrometeorites, and dust storms. In addition lava tubes provide a stable temperature environment and access to underground resources[1].

**System Description:** The dynamics of the hopper jump are a bio-inspired and mimic the jump mechanics of a frog. The hopper will utilize four identical legs with four joints. The "shoulder" joint, which attaches the leg to the body of the rover, is powered by an electric motor. The ankle join between the shin of the leg and the foot will be unpowered and held in place by a spring-damper system. The leg system is shown in Figure 1.

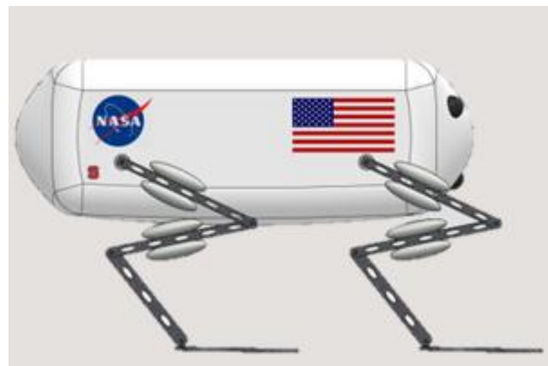

**Figure 1. Preliminary hopper configuration model.**

Two knee joins will be powered by a pneumatic artificial muscle system. A compressor will draw CO2 from the atmosphere in order to actuate muscle system. The hopper will carry an RTG capable of providing 125W of power, and batteries for power storage. The artificial muscles allow the rover to perform jumps up to 300m horizontally, with a maximum vertical height of 150m. During landing, the hopper will experience loads of approximately 17g. The hopper is expected to traverse a minimum of 1km per sol and will accomplish this in a series of 10, 100+m jumps. A fully charged compressor will allow 2-3 jumps, depending on range, and approximately 3 hours will be required to fully recharge.

The entomopter flight theory is based on the emerging area of insect wing aerodynamics. A DelFly-type entomopter design is shown in Figure 2.

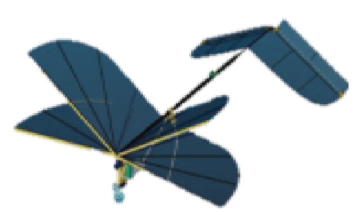

**Figure 2. An entomopter design[2].**

The wings rely on vortex interaction to generate lift, which allows flapping wing systems to operate at low Reynolds numbers. The entomopter will carry a context camera and a mapping package that will allow it to create 3D maps of the surrounding environment. Due to the high altitude operation requirement, the entomopter is not expected to carry any additional scientific payload unless the system mass can be significantly reduced. The entomopter will be battery powered, and will be recharged by the hopper RTG while docked. In order to provide jump directions for the hopper, the entomopter must be able to fly for at least 30 minutes.

The scientific package on the hopper will include mass and point spectrometers for identifying mineral composition and find traces of bioessential elements. A dust analyzer will measure particle size in order to assess their potential impact on mechanical systems and future human explorers. A water vapor sensor will help search for traces of liquid water and a radiation sensor will measure radiation levels on the surface and subsurface of Mars. The operational sensor package on the hopper will include thermocouple for temperature readings, anemometers for wind speed data and pressure sensors to measure atmospheric pressure. The hopper will carry stereo cameras for visual odometry navigation, and will be able to relay high definition imagery for public engagement. The hopper will also include a wireless system to recharge the entomopter between flights.

**Mission Profile:** This mission has been designed assuming a 2026 launch window. The mission profile concept includes two hopper systems and two entomopters. They are to be packaged in an MSL type aeroshell and launched using a ULA Atlas V rocket. The package will land using an enhanced sky-crane system at an altitude of 10km above the MOLA datum. Upon landing, hoppers will move in opposite directions, toward the nearest known lava tube locations.

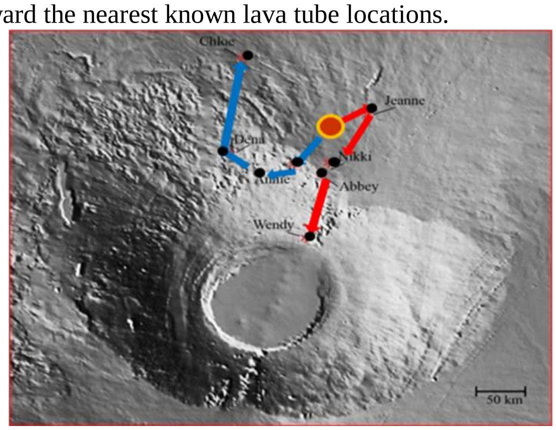


**Figure 3. Mission profile[3].**

Figure 3 shows the proposed mission path. The orange circle is the landing site; red and blue arrows show the travel path for each of the hoppers.

While on the surface, the hoppers will primarily take atmospheric and radiation data, with ability to take spectrometry data between jumps. Entomopter scouts will assist the rovers by exploring terrain in direct vicinity of the hoppers, and direct them to the safest landing locations for the jumps. Upon reaching the lava tubes, the entomopter will enter first and create a 3-D map of the interior near the entrance. This is required due expected debris present at the bottom of the lava entrance. If the area is deemed safe, the hopper will enter the lava tube and begin to collect scientific data. The hopper will search for evidence of past life, as well as assess the lava tube's potential for future human habitation. When sufficient data is collected, the hopper will exit the lava tube and relay the data back to Earth using existing orbiters for communication. Each hopper will traverse over 200km when traveling between lava tube locations at a rate of 1km per day. The mission duration must therefore exceed 200 days. During the mission, both hoppers and entomopters will have to operate with high degree of autonomy in a GPS denied environment. The hoppers are expected to experience temperature ranges between -130° and 30°C over 200 days of operation.

**Technological Improvements:** For the mission to be successful, a number of technological improvements will have to take place before the launch date. An advanced retrorocket based landing system will be required to achieve safe landing at 10km altitude. Innovations in material science are required to produce light weight, wide temperature range alloys and composites. High efficiency compact electronics, power generation and storage devices will also be necessary to achieve efficient high altitude operation on Mars. Further research will have to be done in the areas of flapping wing flight and pneumatic artificial muscle control, in order to achieve better operational efficiency and flight precision. Autonomous operation algorithms will also need to be advanced significantly in order to allow safe vehicle operation when exploring the Martian subsurface.

**References:** [1]Johnson, J.R. (2010) *Mars Science Goals, Objectives, Investigations and Priorities: 2010*.
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