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Micro-Flying Robotics in Space Missions

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ABSTRACT

The Columbia Accident Investigation Board issued a major recommendation to NASA. Prior to return to flight, NASA should develop and implement a comprehensive inspection plan to determine the structural integrity of all Reinforced Carbon-Carbon (RCC) system components. This inspection plan should take advantage of advanced non-destructive inspection technology. This paper describes a non-intrusive technology with a micro-flying robot to continuously monitor inside a space vehicle for any stress related fissures, cracks and foreign material embedded in walls, tubes etc.

INTRODUCTION

The next decades will lead to revolutionary changes in the technology of micro-electronic devices and micro-robotics. The research in miniaturization will lead to innovative technologies achieving greater process intensification and applications, will reduce the cost of space exploration and will increase substantially the ability to perform multiple simultaneous operations.

As cited in the miniaturization of thermal and chemical systems[1], "Miniaturization of electronics over the past few decades has transformed the way we live. The invention of the transistor meant that small, lightweight portable radios could be carried anywhere. Not long ago the idea of chips was revolutionary; today chips make hand-held computers, cell phones, and many other hand-held electrical devices possible. These are examples of distributed technology made possible by miniaturization."

In January 14, 2004, President George W. Bush[2-4] stated, *"We choose to explore space because doing so improves our lives, and lifts our national spirit."* President George W. Bush[5] also said in the Columbia's memorial service at the Lyndon B. Johnson Space Center in Houston, *"This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart."* The President's Vision for U.S. Space Exploration[2-4] calls for the development of a robust space exploration program based on "innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration." To implement this vision, NASA plans an ambitious development of new space vehicles. It will develop a new crew exploration vehicle (CEV) to provide human transportation for missions beyond Low Earth Orbit (LEO), a new cargo transportation vehicle to support the International Space Station and for launching exploration missions beyond LEO, and new nuclear powered vehicles to explore the Jupiter system, outer planets and beyond[6]. The development of these new space vehicles represents the most significant new research into manned spacecraft since the mid-1960s. It will inherit the legacy and most likely the shape of the Apollo Command Module, but will benefit from almost 40 years of technological advances. Given the enormous complexity of the CEV, the pre-launch inspections of the vehicle and its ancillary systems play a crucial role in the success of mission.

Currently, Shuttle launches take months of preparation at the launch pad[7]. Millions of event/items have to be checked till the last count down of launch phase of any given mission. Validating the functionalities of an advanced automation of ground controls, and a propulsion system of new space vehicles before launch operations will require a level of autonomy and health management that is not available today.

The interaction of multiple colonies of robots, and probes in micro, mini and macro level will become a routine requirement of reliability in space exploration. This concept is similar to the concept developed in DARPA in the design of Micro Air Vehicles (MAV)[8-11]. In the following sections, we address a micro-flying robot capability. This capability will support non-intrusive techniques to analyze materials, and other surveillance for the space vehicle and a property of extendibility of micro-flying robots to other future areas in space flight. This capacity will lead to a set of micro-flying robots with an embedded fault detection system, which allows them to act as an advisory system and in many cases as a Supervisor to fix problems detected in the health management of the vehicle. The present micro-flying robot developed by Seiko-Epson Corporation[12-13] uses contra-rotating propellers powered by an ultra-thin, ultrasonic motor with currently the world's highest power weight ratio, and is balanced in mid-air by means of the world's first stabilizing mechanism using a linear actuator. The essence of micromechatronics has been brought together in high-density mounting technology to minimize the size and weight. Each robot can take suitable payloads of photometers, embedded chips for image analysis and micro pumps for sealing cracks or fixing other material problems.

A vision[11] of a collection of micro-flying robots, operating together inside a space vehicle, and fed by information from a variety of sources is a resourceful capability able to address a variety of the most dangerous missions on a global scale. We want to advance an unmanned capability that augments the surveillance of safety in the most difficult situations, creates operational synergy, and provides the kind of leverage that result in true force amplification. The network-based architecture and operating system software that underpin the robots will enable unique functionality for multi-vehicle collaboration, high levels of autonomy, and flexible human intervention, well beyond today's state-of-the-art. Coupled with the enhanced situation awareness that derives from shared information made available by other platforms, the system will dynamically reconfigure and adapt to the threat of faults and failures. The vision is also for an affordable System of Systems, one that uses a common system architecture and operating system that integrates the technologies of instrumentation and autonomy, along with compatible health maintenance systems and reduced support costs. The quest for miniature systems is leading to revolutionary advances in micro-robotics. The 21st century will see great progress in the development and use of micro and nanosystems for space exploration.

MICRO-FLYING ROBOT

Miniaturization, extreme light weight and very low power consumption are fundamental strategic challenges to accomplish future space exploration needs and will impact significantly the mission cost. Different research projects conducted around the world plan to miniaturize flying robots to accomplish specific needs. In Brussels, Alexander Van de Rostyne[14], together with leading suppliers of micro-robotic components, recently developed "*Pixelito*" in 2003. This is a 6.9 gram helicopter-like flying robot with a two-bladed rotor of 148 mm of diameter. Its infra-red control device enables the pilot to have full 4-axis control in the space dimensions. In Oslo, Petter Muren[15], in close contact with the same team of component suppliers, developed the *Proxflyer Micron*, a 6.9 grams very silent and aerodynamically stable flying robot with a coaxial-rotor diameter of 128 mm. It is controlled via a 2-channel radio transmitter and an onboard FM radio receiver. In Georgia Tech., the *Airborne Microflyers* is being developed as a fixed-wing model of a microflyer. Robert Michelson[16] at Georgia Tech Research institute is developing a mechanical insect, known as an "*Entomopter'*." It is based around a new development called a Reciprocating Chemical Muscle (RCM), which is capable of generating automatic wing beating from a chemical energy source. In MIT, *Papa-TV-Bot*, an autonomously hovering mobot with a wireless video camera is being developed[17]. It can operate indoors and in obstacle rich areas where it is able to avoid obstacles automatically.

Recently, EPSON[12] designed a very light micro-flying robot based on the development of a new gyro-sensor that is a mere one-fifth weight of its predecessor, making the world's lightest gyro-sensor and is shown in figure 1. High-density mounting technology is used to reduce weight packaging the micro-robot's two micro controllers, including EPSON original S1C33 family 32-bit RISC. Dynamic lift was boosted by thirty percent by introducing more powerful ultra-thin ultrasonic motors and newly designed optimally shaped main rotors. EPSON added an image sensor unit that can capture and transmit aerial images one each second via a Blue tooth wireless connection to a monitor or ground station and they also devised two LED lamps that can be controlled as a means of signaling.

Figure 1 Micro-flying Robot

The general specifications of micro-flying robot are

- Power: 4.2 V
- Power consumption: 3.5 W
- Dimensions: Diameter: 136 mm, Height 85 mm
- Maximum lift: 17 g/f
- Weight: 12.3 g
- Flight time: 3 minutes

KEY TECHNICAL CHALLENGES OF MICRO-FLYING ROBOT

There are several key technical challenges for the present state of micro-flying robots that can be applied in future space missions. They are as follows:

Figure 2 Micro-flying Robot Demonstration

The aerodynamic characteristics of lift and drag, the payload capacity, and a sustainable flying time of at least 30 minutes instead of the current 3 minutes. The present design as it is shown in figure 2 in a flight demonstration, has to be modified to achieve longer duration flight ranges. The present micro-flying robots operate indoor and need to be redesigned to fly in micro gravity and harsh environments. Modeling the dynamics of the micro-flying robot to the high level of accuracy required for robust performance and simulation will be a unique challenge. A high-fidelity simulation model[18] is required to design the guidance, navigation and control methods that exploit the inherent capabilities of such a small vehicle, as well as for development of real-time simulations for pilot training and system testing. To construct the model, new methods will be needed for identifying the vehicle's dynamic response. The frequency of the dynamic response increases in smaller in size and mass flying vehicles. This response normally exceeds the human's capability for control of the vehicle, and requires a higher level of autonomy. While the present design presently incorporates mechanical augmentation to increase damping of the rotor, an improved flight control system may allow to reduce or eliminate the additional complexity of the mechanical system.[18] Because of the helicopter's tiny size, (see relative size in figure 3) computational- and hardware-intensive navigation processing may have to be accomplished off-vehicle until an autonomous system is developed. Vision-based position estimation using ground-based cameras would fit well into the indoor environment to which the present micro-flying robot is suited. Ground-based computation would also allow deployment of sophisticated path planning, intelligent agents, and obstacle avoidance sensors and software.[18]

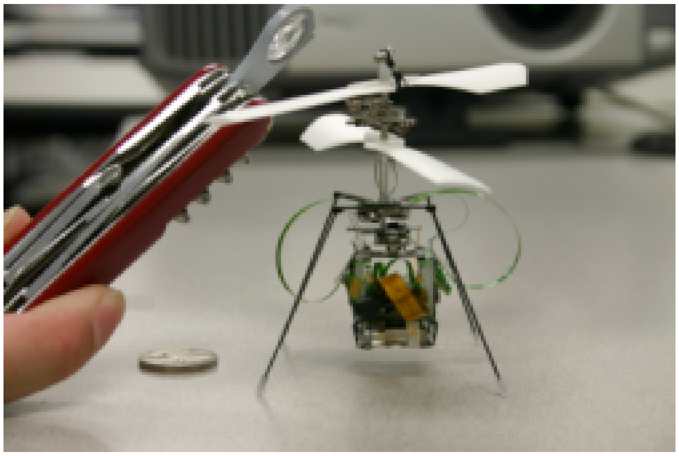

Figure 3 Micro-flying Robot

Present power supply system sustains 3 minutes of flying time. Onboard battery design has to be enhanced in such a way that it can supply power for long duration flight. The battery recharging mechanism has to be developed since there is no recharging mechanism of on-board batteries in its present state. The battery charger can be designed like a mobile base station where the micro-flying robot can land on the charger. The battery charger can be considered a base station, where it can hold micro-Raman spectrometers, computers and other ancillary devices. Even the base station can be another robot, as it is shown in figure 4 below, or an instrument or Crew Exploration Vehicle or astronaut suit.

Figure 4 Micro-flying Robot and Mobile Base Concept

Micro-flying Robot controls: Existing micro-flying robots are controlled by humans or tele-operated. Autonomous on-board controls have to be designed in such a way that there is an autonomous take-off, traversing, recharging of power, stable flight, and smooth landing. The controls have to be designed to withstand harsh environments and micro-gravity. Present communication systems are based on Blue-tooth wireless technology. In a harsh environment, the system will have more interference with the base station. Evolvable antennas and necessary communication system have to be addressed to overcome communication problems. Micro-flying robot's weight and size is a key factor with respect to the payload of the Crew Exploration Vehicle. The micro/nano-sensors are suitably designed to accomplish mission requirements with the least amount of energy expenditure. A plug-in style sensor mating technique to the micro-flying robot may need to be developed. Ancillary instrumentation for power storage, power generation, specific sensor needs, sensor holding and sensor discharging should be developed. Mounting Raman spectrometer probes in the leg of micro-flying robot is a key technical challenge. The probes should be designed in such a way that it can scan in all directions of hardware and surfaces in one pass. Miniaturized instrumentation is needed for conversion of digital and analog signals of Raman spectrometer and instant on board analysis of spectra. Solving the above technical challenges will enable Epson's micro-flying robot to satisfy minimum requirements of specific mission challenges. Distributed collaborative micro-flying robots (flock of robots) to gather data, images and samples will achieve future space mission needs.

ROVERS INSTRUMENTATION

NASA's twin robot geologists, the Mars Exploration Rovers are part of NASA's Mars Exploration Program[19], a long-term effort of robotic exploration of the red planet. These robots provide the base and the examples of the technology that can be develop with Micro-Flying Robots; either as in a collaborative environment or as dedicated machines to specific purposes.

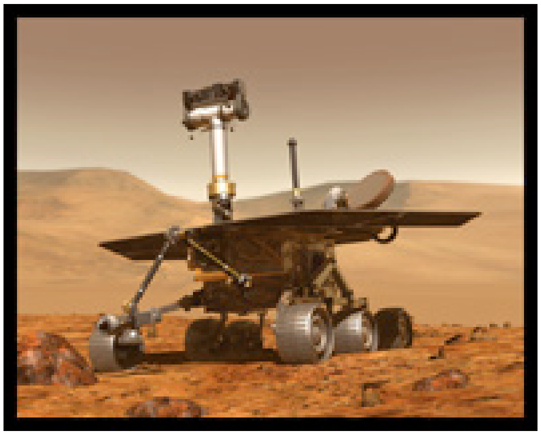

Figure 5 Mars Rover.

Primary among the mission's scientific goals of the Rovers is to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars. The spacecrafts target two sites on opposite sides of Mars that appear to have been affected by liquid water in the past. The sites are at Gusev Crater, a possible former lake in a giant impact crater, and Meridiani Planum, where mineral deposits (hematite) suggest Mars had a wet past.

A goal for the rover is to drive up to 40 meters (about 44 yards) in a single day, for a total of up to one 1 kilometer (about three-quarters of a mile).

Moving from place to place, the rovers were scheduled to perform on-site geological investigations. Each rover is sort of the mechanical equivalent of a geologist walking the surface of Mars, although at a very slow pace. The mast-mounted cameras provide 360-degree, stereoscopic, humanlike views of the terrain. The robotic arm is designed to be capable of movement in much the same way as a human arm with an elbow and wrist, and to place instruments directly up against rock and soil targets of interest. In the mechanical "fist" of the arm is a microscopic camera that serves the same purpose as a geologist's handheld magnifying lens.

The instruments[20] of the Rovers are designed to: (1) provide color stereo imaging and remotely-sensed mineralogical information for Martian surface materials, (2) determine the elemental and mineralogical composition of Martian surface materials, including soils, rock surfaces, and rock interiors, (3) determine the fine-scale textural properties of these materials.

The primary science instruments[5] carried by the rovers for remote sensing are:

Panoramic Camera (Pancam): a high-resolution stereo color panoramic imager for determining the mineralogy, texture, and structure of the local terrain.

Miniature Thermal Emission Spectrometer (Mini-TES): a mid-infrared spectrometer for remote investigation of mineralogy of rocks and soils for identifying promising rocks and soils for closer examination and for determining the processes that formed Martian rocks. The instrument will also look skyward to provide temperature profiles of the Martian atmosphere.

and for in-situ sensing:

Mössbauer Spectrometer (MB): for close-up investigations of the mineralogy of iron-bearing rocks and soils.

Alpha Particle X-Ray Spectrometer (APXS): for in-situ analysis of the abundances of elements that make up rocks and soils.

Magnets: for collecting magnetic dust particles. The Mössbauer Spectrometer and the Alpha Particle X-ray Spectrometer will analyze the particles collected and help determine the ratio of magnetic particles to non-magnetic particles

They will also analyze the composition of magnetic minerals in airborne dust and rocks that have been ground by the Rock Abrasion Tool.

Microscopic Imager (MI): for obtaining close-up, high-resolution images of rocks and soils.

Rock Abrasion Tool (RAT): for removing dusty and weathered rock surfaces and exposing fresh material for examination by instruments onboard.

In addition to these scientific instruments, the rover also carries six engineering cameras [Maki *et al*., this issue]:

- Navigation Cameras (Navcams), two wide-angle monochromatic cameras, also mounted on the PMA.
- Hazard Avoidance Cameras (Hazcams), four fisheye monochromatic stereo cameras, mounted in two stereo pairs on the rover body, viewing forward and backward.

While not formally part of the science payload, these engineering cameras also play important roles in science operations.

RAMAN SPECTROPHOTOMETER

Raman spectroscopy[21-22] is a well-known analytical technique that is recently undergoing a tremendous revival due to technological advances in lasers, detectors and spectroscopic optical systems. When light is scattered by any form of matter, the energies of the majority of the photons are unchanged by the process, which is elastic or Rayleigh scattering. However, about one in one million photons or less, lose or gain energy that corresponds to the frequencies of the scattering molecules vibration. This can be observed as additional peaks in the scattered light spectrum. The process is known as Raman scattering and the spectral peaks with lower and higher energy than the incident light are known as Stokes and anti-Stokes peaks respectively. Most routine Raman experiments use the red-shifted Stokes peaks only, because they are more intense at room temperatures. The availability of intense laser light sources from the 1970's onwards, and improved detector technology, with the increased Raman signal intensities resulting from these developments, started the technique's revival. Raman spectrometer hardware also started to upgrade, with the adoption of the multi-channel, silicon diode array and then the charge-coupled device (CCD) detectors developed for imaging technology. Prior to this, a point detector such as a photo-multiplier tube, was used to collect light from each point in the spectrum in turn, rotating or scanning the spectrograph. This was a slow process, and collecting spectra took tens of minutes to several hours. However, the cooled CCD detectors now used can collect a wide spectrum almost instantaneously without scanning the spectrograph. The spectrograph is simply parked at the centre of the wave number region of interest and the CCD camera acquires the spectrum until good intensity is obtained, usually in a few seconds.

Another improvement to the Raman systems, ten to twenty years ago is the addition of the holographic notch filter used to eliminate the Rayleigh scattering. Prior to the use of notch filters (or sometimes, interference edge filters), two successive spectrograph gratings were employed to filter the laser light from the Raman spectrum. Such so-called triply dispersive instruments, whilst allowing good precision and permitting acquisition of the Raman scattering from only a few wave numbers away from the excitation line, are complex and have a much lower throughput (sensitivity) than the single-grating systems. In contrast, the notch filter is inexpensive, easy to exchange when laser wavelengths are altered, and allows most of the Raman spectrum, to within about 50 cm^{-1} of the laser line or sometimes even less, to be collected. Such instruments are called singly dispersive. Raman spectra can now be acquired in real-time from almost any material in the world. It is a non-destructive and non-invasive method: samples inside glass bottles or transparent plastic containers such as drug packages can be analyzed without breaking the seal or risking contact with toxic or delicate samples.

There are two methods for analyzing the Raman spectrum of a sample: using a dispersive spectrograph with a diffraction grating or employing a Fourier-Transform (FT) spectrograph. The latter technique is often done using an accessory to a near-IR capable FT-IR spectrometer system, although to ensure adequate performance in the very near IR region used for FT-Raman, very high quality (gold coated) optics and InGaAs detectors are also required and the system becomes considerably more expensive than a standard FT-IR bench. Also, a rather powerful and expensive laser, typically a 1~5 Watt CW YAG of 1064nm, must be used (in contrast, a dispersive Raman Spectrometer will operate with only a few percent of this power level). Raman scattering originates from molecular vibration modes in the material and produces spectral emission at a constant wave number shift from the exciting light, so a green laser of 532nm should give a qualitatively identical spectrum to that obtained from 785nm light. The main system hardware for Raman spectrometers is the laser light source, the microscope sample chamber and the spectrograph or polychromator.

Light in a narrow, collimated beam from the excitation laser unit passes a line filter to remove any unwanted laser lines and sidebands (such as from pumping light in a diode laser, or a plasma lines in a gas laser), before passing via the beam splitter into the microscope. Additional optics including a macro beam mirror placed before the microscope, allowing macroscopic illumination of the Sample (dotted green line). Depending on the design of Raman Spectrometer, instruments may have more than one laser and laser selection optics. Co focal micro-Raman systems tend to minimize fluorescence signals because the objective lens focuses only on a small volume of material instead of the larger fluorescing volume actually excited by the laser in figure 6. Macro-Raman sampling acquires both the small Raman signal and much of the larger fluorescence background. Co focal micro-Raman can reduce fluorescence problems by virtue of the very small sample volume in the objective lens focus (green). The volume of sample producing fluorescence (red) is much greater but is largely ignored as the co focal aperture limits the range of focus contributing to the spectrum. In this figure 6, only light from within the green in-focus region is analyzed. The influence of fluorescence is greatly decreased.

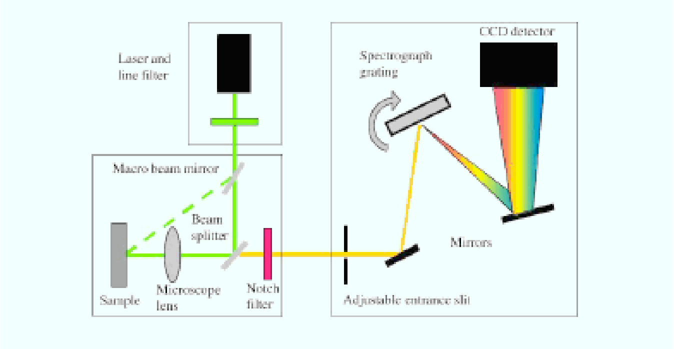

Figure 6 Raman Spectrophotometer.

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Microscopic impurity particles can be detected even when embedded in a different (transparent) matrix because the different Raman signals are resolved by the microscope (spatially) and spectrometer (spectrally). For situations where the sample cannot be taken into the instrument, the excitation laser and scattered Raman signal can be fiber-optically coupled to the spectrometer. This scenario will be generally applicable to pre-launch inspection of the materials, tubes and other hardware in the CEV. Probes allow powerful in-situ Raman measurements at a range of excitation wavelengths and with semi-micro capabilities using a long working distance lens and built-in color CCD-TV camera for sample viewing. Alternative probes allow for immersion measurements in various liquid samples or in corrosive or other hazardous environments such as nuclear propellant tanks and other hazardous areas in the CEV. The Raman spectra and representative microscopic images can be used to characterize any type of contaminants or cracks. In the CEV, nano technology will play a crucial role in developing nanotubes. The primary method of analysis of nanostructures is micro-Raman spectroscopy. The advantage of Raman spectroscopy is reliability, non-destructive and microscopic sample size. The micro-Raman spectrometer will be mounted on a micro-flying robot, which will keep constant monitoring of all hardware before launch of the CEV.

CONCLUSION

Micro-flying robot technology can be adopted to address a given mission needs from pre-launch inspections to on-board inspection and health monitoring of a CEV. This technology combined with micro-Raman spectrometer probes may monitor stress related cracks and fissures by providing a vertical and horizontal scanning of the materials and hardware. Micro-flying robots can also perform the function of an assistant robot for a primary robot, where the primary robot may control planning and scheduling of all instrumentation of the micro-flying robots in inspection missions and in sciences missions. The micro-flying robots can support human missions as robotic assistance. Since micro-flying robot development is at its initial stages, new innovative concepts are needed to achieve NASA's mission needs and goals.

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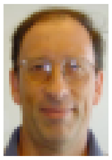

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