NASA NDE Applications for Mobile MEMS Devices and Sensors

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ABSTRACT

NASA would like new devices and sensors for performing nondestructive evaluation (NDE) of aerospace vehicles. These devices must be small in size/volume, mass, and power consumption. The devices must be autonomous and mobile so they can access the internal structures of aircraft and spacecraft and adequately monitor the structural health of these craft. The platforms must be mobile in order to transport NDE sensors for evaluating structural integrity and determining whether further investigations will be required. Microelectromechanical systems (MEMS) technology is crucial to the development of the mobile platforms and sensor systems. This paper presents NASA's needs for micro mobile platforms and MEMS sensors that will enable NDE to be performed on aerospace vehicles.

Keywords: Micro robots, MEMS, NDE, sensors.

1 INTRODUCTION

Currently, NASA uses visual inspection, thermography, ultrasonics, eddy current, and THz methods when nondestructive evaluation (NDE) of aerospace vehicles is required. These methods are successful when applied to accessible regions of the vehicles, but they cannot be used in inaccessible areas. Therefore new systems are needed that are reduced in size/volume, mass, and power consumption. The devices must be mobile to scan the structures of aircraft and spacecraft and provide adequate spatial coverage for monitoring their structural health. The systems must also be autonomous, able to locate defects and determine whether further investigations are required. Microelectromechanical systems (MEMS) technology will be used to develop the mobile platforms and sensor systems needed to achieve these goals.

2 NDE SENSOR APPICATIONS

2.1 Imaging

Although the most widely used NDE technique is visual inspection, many areas within spacecraft and aircraft are inaccessible for imaging. Reducing the size of an inspection system allows better coverage. Detecting cracks, corrosion, missing fasteners, and estimating damage can be performed by miniaturized camera systems on a moving platform. In addition to standard imaging techniques, thermography can be used to detect defects below the surface. Space Shuttle sample panels of reinforced carbon-carbon have been inspected for damage using thermography. The system relies on sunlight and shadowing to eliminate a need for flash lamps and to reduce power, weight, and costs [1]. Another system without flash lamps uses acoustic energy to generate heat that is imaged with an infrared camera [2]. Further reductions using MEMS technology would enable free-flying systems to scan the vehicle autonomously. Current thermal imaging systems generate a modest amount of data, roughly 160 Kbytes per frame at a rate of 60 Hz for about 850 frames. The 145 MB data volume is challenging for MEMS sensor systems.

2.2 Ultrasonics

Ultrasonic waves provide a variety of mechanisms for performing NDE on structures. In contact ultrasonics, transducers placed in contact with the structure excite and measure the ultrasonic waves. For non-contact applications, lasers can generate ultrasound waves through thermoelastic expansion [3]. In both cases the ultrasonic waves propagate within the structure to detect fatigue cracks, delaminations, and subsurface damage of composites. Airborne ultrasonic waves are also being investigated for leak detection. In this case, the system does not create an ultrasonic wave; rather, it monitors for characteristic ultrasound signatures that are indicative of a leak. The data rates for ultrasonic systems require sampling rates on the order of several mega samples per second.

2.3 Eddy Current

The recent discovery of cracks in Space Shuttle Primary Reaction Control System thrusters has triggered the development of new NDE techniques utilizing eddy current sensors. Cracks are detected by scanning the thruster with dual frequency, orthogonal, eddy current probes [4]. This technique can detect hidden cracks to a depth of 0.060". In general, the data rates from eddy current systems like this one are quite low (1600 bytes per second), making, the systems candidates for miniaturization using MEMS technology. An existing MEMS eddy current sensor may prove suitable for NDE applications [5]. The sensor consists of two stacked planar coils and a Ni/Fe Permalloy core, and it can detect surface cracks in aluminum.

2.4 Terahertz

The frequency range from 0.1 to 100 THz is being exploited to deliver a new class of NDE instruments. This frequency range has better penetration than infrared, has higher resolution than microwave radiation and is less hazardous to biological tissue (due to less photon energy) than X-rays [6]. For aircraft applications, THz instruments can detect bubbles in carbon reinforced stringers [6]. For space applications, THz systems have detected 0.13 mm deep, corroded areas underneath Space Shuttle tiles [7]. Furthermore, future space habitats may be inflatable rather than rigid structures (Fig. 1.). THz imaging was able to detect small cuts and holes in the Kevlar restraint layer and small holes in the bladder layer of in an inflatable habitat module [8]. The same testing verified superior results from THz when compared to thermography or ultrasound methods.

Figure 1. Model of inflatable lunar habitat concept.

A miniaturized THz system will have many applications in addition to those of NDE. However, reducing the size of a THz system will also have many challenges, such as the data volume. A THz system can generate about 50 Mbytes during 15 minutes of operation. Although this volume of data sounds large, it can be stored on a single memory chip.

3 MICRO MOBILITY PLATFORMS

Many NDE applications require the scanning of inaccessible areas of a structure during evaluation. Therefore, almost all forms of locomotion are of interest for NDE applications. Swimming robots exist but will not be considered here because the only fluid available is the fuel, and, while NDE of fuel tanks is worthwhile, robots have not yet been developed for this application. NASA is interested in swimming robots, however, for the exploration oceans below the ice of Jupiter’s moon Europa.

For NDE applications, crawling, walking, climbing, flying, and even micro rockets may be employed. Many of the micro robotic platforms that could be used for structural integrity evaluations are inspired by existing biological forms. Pfeifer provides a list of biologically inspired robots with the biological analogues [9]. To help in developing efficient microrobots, researchers are studying insects to gain knowledge of environmental interactions in the micro world. Others are researching the possibility of adding sensors to living insects to create small hybrids that can perform as intelligent sensor systems [10]. In addition, researchers are not stopping at the micro level, nanoelectromechanical systems are being developed as well. These systems will interact with nano-scale objects using nano-sized devices [11]. As these technologies mature, more tools and platforms will become available for developing mobile NDE platforms.

3.1 Crawling

The simplest form of locomotion is crawling. Researchers have achieved a crawling motion with an untethered MEMS scratch drive actuator [12]. The device can move forward and turn. However, a surface of insulated interdigitated electrodes is required to motivate the device capacitively. On a larger scale, an earthworm-like, bio-mimetic, wireless robotic platform has been demonstrated [13]. This device relies on shape memory alloy as an actuating mechanism for linear motion. Another example of earthworm-like locomotion combines linear actuators based on DC motors with wireless control electronics [14]. This creates a micro-robotic endoscope for non-invasive medical applications. An advantage of crawling motion is that it can carry larger payloads for the same amount of energy, compared to other forms of locomotion. However, worm- or snake-like robots could effectively scan portions, but not all, of the internal structure of an aerospace vehicle.

3.2 Walking

Crawling might suffice for medical applications, but walking or climbing would be better for scanning a structure like the interior of a wing. One of the first autonomous micro robots that incorporated legs was developed at Berkeley [15]. The robot has two legs and drags its body behind, but it contains a processor and is solar powered. Another robot from Berkeley has increased the number of legs to six [16]. This robot moves three legs at a time to maintain a tripod stance. A micro robot was created from two cilia array chips [17]. Each chip has an 8x8 array of cells, each cell consisting of four thermal bimorph actuators or cilia. The large number of legs allows this micro robot to carry a load of 3.524g. An eight-legged micro robot has been demonstrated, also. It carries a 2.5 gram load, which is 30 times the weight of the robot [18].

Full coverage of the interior spaces of an aerospace vehicle requires all surfaces to be scanned, so walking or crawling micro robots may also need to climb. Mimicking a gecko’s foot movements, specifically the curling and uncurling of toes, lets one micro robot climb walls [19].

3.3 Flying

Flying micro robots could scan both the exterior and the interior of structures. A four bladed (1.5 cm each) micro helicopter called the Mesicopter is being developed for future NASA MARS missions (Fig. 2.) [20]. Helicopters of this size could prove useful for NDE applications as well. The US Air Force is investigating the biologically inspired MEMS wings that flap [21]. Thermally actuated by an external laser source, the small flapping wings have yet to achieve flight. A micro insect-inspired design based on the honeybee is also being developed [22]. This effort has not yet flown either. However, a micro robotic insect called a fly has been fabricated and flown [23]. The fly weighs only 60 mg and has flown with the aid of guide wires for stability control.

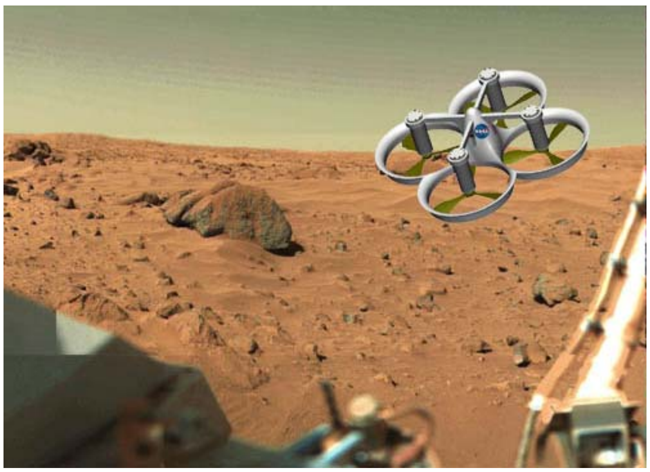

Figure 2. Artist impression of MARS exploration using Stanford's Mesicopter.

3.4 Micro Thrusters

To make space exploration more affordable, NASA, DARPA, and other space agencies are investigating small spacecraft. MEMS technology has been used extensively to create the miniaturized propulsion systems required for this new class of space vehicles. A thruster has been developed that combines MEMS and nanoparticles to create nanoparticle field extraction thrusters (nanoFET) [24]. At NASA's Jet Propulsion Laboratory micro versions of cold gas systems, field emission electric propulsion (FEEP) devices, micro pulsed plasma thrusters (PPTs), and colloid systems are being developed for future NASA missions [25]. Other types of micro thrusters are being investigated around the world, including a vacuum arc thruster, laser ablation thruster, micro ion thruster, micro resistojet, vaporizing liquid mircothruster, digital propulsion, monopropellant thruster, and radioisotope propulsion [26]. Any one of these methods may be the key to a new mobile platform for NDE applications both in space and on Earth.

4 ISSUES

Many issues and challenges must be overcome when reducing instrument sizes into the micro world. Some of the issues include the amount of processing available on board the device, wireless communications, and the level of autonomy that the device exhibits. The location of the device must be known with enough resolution for accurate defect- or damage location. Some measurements require precise device location during the mapping of large areas to ensure adequate spatial coverage. The search pattern used for achieving coverage will have to be determined. Will random searches suffice or will more elaborate search patterns be needed?

Another issue: whether to develop modular devices or specialized devices for each type of measurement. Modular devices with modular sensors may reduce the costs overall for devices in large numbers, while specialized devices may reduce the costs associated with a specific measurement. Energy-harvesting micro robots have already been developed. Solar cells power the walking micro robot [15], and the flapping wings are powered by an external laser [21]. It has been suggested that some of the mobile robots could gather energy from external stations and deliver that energy to internal robots [27]. Obviously, research into micro-robotic energy scavenging and energy storage will need to continue in the foreseeable future.

During the scanning of a structure, the stability of the platform used during measurements becomes an issue. The platform might remain stationary for some applications, but it must maintain stability during movement for others. Finally, platforms must not outgas or pollute the environment within structures or coat sensitive optics and devices external structures. This may not be a problem with most forms of locomotion, but thrusters that expend mass to create reaction forces may not be suitable for some applications.

5 CONCLUSIONS

NDE is required to ensure the safety of aerospace vehicles and their passengers. MEMS technology can play a crucial role in the development of smaller, lower power NDE sensors and agile mobile platforms. Adding mobility will increase the coverage of NDE instruments in previously inaccessible locations within aircraft and spacecraft. Imaging, thermography, ultrasonics, eddy current, and THz sensor systems are all candidates for miniaturization, using MEMS technology. These small instruments could then be integrated on mobile micro-robotic platforms. The micro robots could use crawling, walking, flying, and even micro rockets to move around the interiors and exteriors of aerospace vehicles. Despite an identified need for these micro robotic NDE instruments, NASA does not have the resources to develop them all. NASA encourages partnerships, including those with universities and industry, to aid in the development of the next generation of NDE instruments.

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