Advancements in Automatic Leak Detection and Repair Onboard Pressurized Space Environments

Project Final Report

Submitted to

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1 Introduction

While considerable research, experimentation, and analysis has been performed toward identifying and characterizing both natural and human made Space debris, the likelihood of impact with “active orbiting objects” remains a clear and present danger. As the race for Space continues to expand through the 21st century, Space debris will pose a serious threat to crew safety aboard the International Space Station (ISS), the Space Shuttle, and Crew Exploration Vehicles (CEVs).

The Department of Defense spends millions of dollars each year tracking orbiting Space debris to avoid catastrophic collisions with both existing and newly inserted satellite systems. The 1st Space Control Squadron of the U.S. Air Force Space Command Center (SCC) inside of Cheyenne Mountain in Colorado is currently responsible for tracking, identifying, and cataloging all Earth orbiting artificial satellites. SCC provides “collision avoidance analysis” to NASA throughout mission duration. This support is provided to both the ISS and the Space Shuttle, and will continue to be the main source for providing collision avoidance data required in CEV navigation.

The SSN has been tracking Space objects since 1957 when the former Soviet Union started the Space race with the launch of Sputnik I. Since then, the SSN has tracked more than 24,500 Space objects orbiting Earth. This includes both operational satellites and Space debris. Of that number, the SSN currently tracks over 13,000 orbiting objects. The remaining objects are believed to have re-entered Earth's turbulent atmosphere and disintegrated, or survived re-entry and impacted the Earth. About 7 percent of the tracked objects are operational satellites, 15 percent are rocket bodies, and about 78 percent are inactive satellites and satellite fragments of all sizes. The Space objects now orbiting Earth range from satellites weighing several tons to pieces of spent rocket bodies weighing only 10 pounds. The SSN tracks space objects which are 10 centimeters in diameter (baseball size) or larger.

Figure 1: Low Earth orbit Space debris
SSC estimates about 84 percent of the identifiable debris are approximately 800 kilometers above Earth. This is over twice the nominal orbiting altitude of the ISS and the Space Shuttle. It has been estimated that “the likelihood of collision between a piece of debris (10 centimeters or larger) and the ISS or the Shuttle is 1 in 10,000 years, in the worst case.” Again this does not include objects smaller than baseball sized objects. The probability of collision with debris smaller than baseball size is obviously much higher because they cannot be tracked with available sensors.

1.1 Space debris impact

Photographs of debris impact illustrate the threat and danger posed by orbital debris. The photographs are from the NASA/Johnson Space Center Orbital Debris website and are reproduced in this paper for purposes of discussion. Figure 2 is the photograph of a window pit from Shuttle mission STS-007. The pit measures approximately 1mm in size.

Figure 2: Small debris impact from Shuttle mission STS-007

Figure 3 shows a punctured antenna on the Hubble Space telescope caused by debris impact.

Figure 3: Punctured antenna on Hubble Space telescope
While there are many sources for collecting data pertaining to Space debris impact, data from the Long Duration Exposure Facility (LDEF) is proof of the existence of undetectable debris. LDEF, a bus-sized spacecraft was left in low Earth orbit (LEO) for approximately 5.7 years before being retrieved by Space Shuttle Columbia in January 1990. Over 20,000 impacts have been documented on LDEF, approximately 1,000 of which have been chemically analyzed in an attempt to determine the origin of the projectile. A close-up view of a panel from the LDEF spacecraft is shown in Figure 4.

![Figure 4: Close-up of an LDEF Panel](image)

SolarMax, a Solar observatory operated by NASA was used to study the Sun’s changing activity in its 11-year cycle of activity. The observatory had an orbit of 566 km x 569 km, at a 28.5° inclination. Figure 5 shows a hole punched through the panel of the SolarMax experiment.

![Figure 5: Hole caused by Space debris in SolarMax experiment](image)

From the appearances of debris impact shown in Figures 2-5 it is very clear that in addition to the large objects being tracked, there are tens of thousands of natural micrometeorites and human generated debris that cannot be tracked and pose a very serious threat. These are smaller than 10 cm in size and include fragments of disintegrated satellites, paint flakes and screws from
satellites, and other undetectable Space debris. In the event of an impact, there is presently no means to detect how many leaks have occurred and where the leaks are located. Failure to provide mitigating technologies for such emergencies has the potential for a catastrophic event in the manned Space Program.

1.2 NASA’s approach to Space debris problem

In the current emergency depressurization response by NASA, on-board atmospheric pressure sensors enable initial detection of a significant leak above normal losses, and handheld ultrasonic tools aid in locating internal leaks. New improvements in detection include a fiberscope that allows access to difficult areas. Efforts also continue to identify a new nitrogen pressure sensor and infrared camera. Due to surrounding structures, audibly active mechanisms, and normal atmospheric flows, locating small leaks can be difficult. When an actual leak site is found, patch kits are on orbit that might temporarily seal a small leak from inside the ISS modules. More effective and permanent internal and external patches are being studied and are discussed later.

Crew training and ground operational procedures to react to a depressurization event include: verifying valves are properly closed, listening with sensitive audible sensors, isolating portions of the cabin, conducting internal repairs, and to evacuate the ISS if warranted. The primary evacuation module is the Soyuz module that is constantly docked at the ISS.

An international group led by the ISS Program is coordinating plans for development of improvements to the leak detection and repair capabilities. This includes both internal and externally applied solutions. While the current list of ISS relevant topics includes many aspects of Space vehicle construction, the topic of “Improved Methods for Air Leak Detection” appears principal among all topics being addressed. This paper addresses a novel approach to air leak detection and a revolutionary technology to fix leaks that might otherwise pose an overwhelming task for the Crew.

2 Automatically Detecting and Locating the Leak Source

It was originally proposed that a Repairbot should locate the leak source by determining the direction of airflow relative to itself and following the path of the air towards the leak source. While the robot may be able to effectively accomplish this task when in close proximity to the leak, such a sensor system may have trouble detecting flow patterns in the case of minute leaks, especially when far away from the source. When an emergency is occurring such as a rapid depressurization, every second counts and even if the sensor swarm was able to effectively navigate itself towards the leak using the surrounding airflow, this would still take valuable time. It is now believed that sensing the pressure shockwave that is produced at the instant of rupture is fundamental to locating the leak point. The velocity of a pressure wave propagating throughout the environment is approximately 346 m/s, equivalent to Mach 1.

Figure 6 conceptually illustrates the shape of the steady-state and transient pressure waveform that can be expected without any reflections. Reflections cause the sensor output to “spike” to each received wave front. In the steady-state, the pressure sensed is sinusoidal with an average
pressure equal to 14.7 psi, the normal atmospheric pressure to sustain human life. At the instant of rupture in the pressurized containment, a shockwave propagates from the leak source. Arrival of the wave front at a pressure sensor causes the pressure to rise sharply to a peak value and decays rapidly towards the normal atmospheric pressure. Depending upon the leak rate, the pressure continues to drop until the interior of the pressurized environment exhausts all the air into the vacuum of Space. The shape reflects the anticipated transient caused by the pressure wave and the resulting pressure decay based upon leak rate. Small leaks such as that initially caused by a minute crack for example can evolve into a larger leak and cause faster pressure decay.

Such information is useful in determining the size of leaks, and to aid the Crew in estimating the time remaining to perform repair or evacuation operations.

![Figure 6: Pressure transient characteristic](image)

Measuring the relative time of arrival of the wave front at sensors located in a grid provides the distance from the pressure orifice. In this context, a pressure sensor net concept is explored as a method to rapidly locate unidentified leak sources. The computed coordinates of the leak can then be quickly provided to both Mission Control and the Crew. Once the leak source coordinates are precisely determined, this opens up several possibilities for both Crew and other automated means for leak repair.

2.1 Sensor net for automatic leak location

Figure 7 illustrates a sensor net arrangement of piezoelectric sensors. Each sensor in the net is identified by its geometrical coordinates within the Space module. Various possibilities for leak locations within the grid are illustrated along with contoured paths of the propagating shockwave.

From Figure 7(a) it is obvious that if the leak is in the center of a square grid of sensors, the arrival times of the wave front are the same at each sensor. Hence the leak location must be at the center of the square grid. Since a square grid arrangement may not always be possible, any
arrangement of grids formed by four sensors would work equally well. Figures 7(b), 7(c), and 7(d) illustrate other leak locations where one of the four sensors is triggered first. The first of four sensors triggered provides a reference for computing the relative time of arrival of the wave front at the remaining three sensors.

Figure 8 illustrates the 2-D geometrical relationships between the four sensors surrounding a leak point L.
The distance measures are computed on the basis of selecting the first four sensor outputs triggered by the shockwave, and computing the relative time of arrival of the wave front relative to the first sensor output.

Referring to Figure 8, the distances between the leak point L and the sensors can be written as:

\[
\begin{align*}
    d_1 &= \sqrt{(x-x_{S1})^2 + (y-y_{S1})^2} \\
    d_2 &= \sqrt{(x-x_{S2})^2 + (y-y_{S2})^2} \\
    d_3 &= \sqrt{(x-x_{S3})^2 + (y-y_{S3})^2} \\
    d_4 &= \sqrt{(x-x_{S4})^2 + (y-y_{S4})^2}
\end{align*}
\]

(1)

Since the distance between the leak point and the nearest sensor is unknown, we denote the arrival time \( t_{S1} \) of the wave front at sensor \( S_1 \) equal to zero. This allows computation of the relative time of arrival \( \Delta t_{S2}, \Delta t_{S3}, \Delta t_{S4} \) as the arrival times of the wave front at each of the 3 sensors. Since distance equals the product of velocity and time, we can compute the distances \( (d_2-d_1), (d_3-d_1), \) and \( (d_4-d_1) \) in terms of the relative times of arrival as:

\[
\begin{align*}
    v\Delta t_{S1,S2} &= \sqrt{(x-x_{S2})^2 + (y-y_{S2})^2} - \sqrt{(x-x_{S1})^2 + (y-y_{S1})^2} \\
    v\Delta t_{S1,S3} &= \sqrt{(x-x_{S3})^2 + (y-y_{S3})^2} - \sqrt{(x-x_{S1})^2 + (y-y_{S1})^2} \\
    v\Delta t_{S1,S4} &= \sqrt{(x-x_{S4})^2 + (y-y_{S4})^2} - \sqrt{(x-x_{S1})^2 + (y-y_{S1})^2}
\end{align*}
\]

(2)

where the velocity of sound \( v = 346 \text{ m/s} \). A solution for the leak-point coordinates involves solution of the nonlinear equations in Equation (2).
2.2 An Example

Referring to Figure 8, we assume a set of 4 piezoelectric sensors enclosing a 1-m² area with coordinates in meters represented as (0,0), (1,0), (0,1), and (1,1) corresponding to sensors \( S_1 \), \( S_2 \), \( S_3 \), and \( S_4 \), respectively. For a leak \( L \) located at coordinates (0.25, 0.25) relative to sensor \( S_1 \) which we will assume as unknown for the moment, the arrival times of the P-wave \( \Delta t_{S2}, \Delta t_{S3}, \Delta t_{S4} \) at sensors \( S_2 \), \( S_3 \), and \( S_4 \) relative to sensor \( S_1 \) are computed to be 1.263 ms, 1.263 ms, and 2.044 ms based on the velocity of the pressure wave, namely \( v=346 \text{ m/s} \). In this example, the arrival times at sensors \( S_2 \) and \( S_3 \) are equal due to the symmetry around the selected leak point. Substituting all known values and solving the nonlinear equations yields the leak-point coordinates as (0.25, 0.25) meters with reference to the (0,0) point.

A sensor net such as the one proposed can provide a means for a visual 3-D display of the pressure distribution inside the Space Station. Such a visual display would provide a real-time “breathing” map of several modules of ISS which might be color coded similar to a Doppler map to show the pressure gradient. This is extremely useful information inside the ISS and CEVs as it provides a clear view of the interior environment of the pressurized modules. The sensor outputs can easily be configured to trigger an annunciation in the event of a leak. As soon as the leak is detected and a rapid depressurization alarm is triggered, Mission Control has the ability to quickly analyze the disturbance data and determine which module of the Space vehicle is the source of the pressure leak. This would allow quick isolation of the damaged module until repairs can be performed. The specific location of a leak in a given module is based upon the sensitivity of the sensors in the “net”.

The minimum distance two sensors can be placed from each other is directly dependent on the sampling rate of the given pressure sensors. Assuming the velocity of the pressure wave to be 346 m/s, it would take approximately \( 720 \times 10^{-6} \) seconds for the pressure wave to traverse the distance between any of the two pressure sensors in the setup described above. Modern piezoelectric sensors provide microsecond response times and resonant frequencies in the hundreds of kHz, with little overshoot or ringing. Sensors designed with smaller diaphragms allow greater spatial resolution for narrow shock waves. Assuming a sensor sampling frequency of 100 kHz, up to 72 data points can be acquired from each sensor during the time the pressure wave is traveling between sensors. A sensor with this sampling capability should be more than sufficient in attaining the required resolution needed to determine the direction and origin of a propagating wave.

The effective “sample resolution” of a sensor grid as a function of the time delay between the triggering of the sensors and the sampling rate of the sensors, is expressed in Equation (3).

\[
N = S(D/V)
\]  

(3)

where, \( N \) is the number of samples sensed, \( S \) is the sampling rate (kHz), \( D \) is the distance between sensors, and \( V \) is the velocity of sound, 346 m/s. As the sampling rate of the sensors increases, the time delay between the sequential triggering of sensors can be more precisely determined and therefore the coordinates of the leak can also be more accurately determined.
3 Autonomous leak repair system

A dynamic pressure sensing net capable of locating a leak source is only the first step toward the development of a fully autonomous leak detection and repair system. Such a system would greatly improve the safety of space exploration by allowing Crew to focus solely on their own safety as opposed to putting themselves in direct danger while attempting to locate and repair a leak in their environment. On the ISS the Crew could seal themselves inside a “self-sustaining” emergency module that is isolated from the rest of the leaking environment until a repair has been made and nominal living conditions have been reestablished.

The simplest and most reliable way to repair a leak is to use a textile-like liner composed of carbon nanotubes covering the entire inner wall of the Space vehicle or habitat. At the instant of rupture, anything in close proximity is extruded out of the orifice. “Fluffy” hair-like nanotube clusters close to the wall surface are attracted into the leak source. With their orientation along the axial length of the orifice, the leak source is densely populated by nanotube fibers and therefore has the propensity to plug the leak. Nanotubes have superior elastic properties. The process of extrusion through the leak creates a fiber strand that adds strength and permanence to the repair location.

Carbon nanotubes also have excellent electrical characteristics for charge collection and offer the potential for developing highly sensitive acoustic sensors capable of detecting leaks caused by microscopic cracks. The idea therefore is to form a net-like fabric wherein carbon nanotube clusters act as acoustic sensors. With their close proximity to the inner wall the detection of microscopic cracks is made possible by sensing ultrasonic or even hypersonic frequencies caused by microscopic leaks. While a textile-like liner composed of carbon nanotubes is the simplest and most fundamental way to fix a leak, the focus of this research was on a more exotic means of automatic leak repair.

3.1 Sensor Swarm for Automatic Leak Repair

When a leak occurs, it is theorized that the array of piezoelectric sensors would be sequentially triggered, starting with those in the module where the leak occurred. Using specialized software the real-time sensors outputs are 3-D mapped with interfaces to visual displays and emergency alarm triggers that are available to both Mission Control as well as the Crew. Other sensors capable of determining the direction of air molecules in motion can be placed in the node modules of the ISS, which are central modules with hatchways to other modules on all six sides. By determining the direction of the air flowing towards the leak, these additional sensors would provide verification of the telemetry provided initially from the piezoelectric pressure sensor grid. The direction of the flow of traveling air molecules can be determined using a technology that ionizes the air and utilizes a surrounding ion detector array to measure the ion concentration in the air relative to the positive of the ionization source.

Once the specific leaking module has been determined, it is envisioned that some form leak-repairing robotic technology would be released to make temporary or even permanent repairs of the leak source. In a microgravity environment such as the ISS, a swarm of small robotic sensors could be released from a containment in the direct vicinity of the leak and use the motive forces
provided by the air currents to travel to the leak and repair it. In reduced gravity environments or in the case of slower leaks, simple propulsion systems or adhesive appendages would allow the sensors to traverse the terrain as required. Other leak repairing technologies such as a larger single robot could also be used to crawl throughout the interior or even exterior of the Cabin surface toward the leak source, but the numerous options fall outside the scope of the paper.

A conceptual illustration of a possible sensor swarm technology is shown in Figure 9.

Figure 9: Concept of swarm repair sensors

The basic idea illustrated is that a mother sensor with sensitive “ear drums” near the vicinity of the air leak is alerted of a pressure leak. The alert comes from the primary sensor net monitoring system in terms of the Cabin (x,y,z) coordinates where the leak has occurred. These coordinates received by the mother sensor CPU will activate the sensor swarm inside the mother sensor. It can be envisioned that each sensor in the repair-swarm has the capability to be programmed to the destination (x,y,z) coordinates using RFID technology. Simultaneously, the swarm is prepped by inflating each sensor to provide a means for propulsion. Once prepped, the swarm is released with both directional information as well as an air-propulsion mechanism. The idea here is similar to an inflated balloon that is let loose. However the repair-swarms will have the capability to provide vector thrust that guide the swarm toward the leak coordinates.

Each mother sensor is equipped with a pair of Cerci-like probes to detect air-flow in the Cabin. Cerci are the minute appendages that cockroaches have to sense air motion and detect air leaks. This concept will allow the mother sensor to also program the air-flow information on each repair-sensor so their internal propulsion can be used effectively in moving along the air-flow towards the leak point.
3.2 Swarm geometry in leak verification

Compared to the sensor net leak detection scheme where the leak coordinates can be detected in 2-D since the leak point lies in a plane along the walls of the Cabin, the swarm geometry for leak verification is in 3-D space. We assume a mother sensor and four daughter sensors in the leak verification sensor swarm network, as shown in Figure 10.

The distance between leak point P and sensor S1 is:

\[ (x_p - x_1)^2 + (y_p - y_1)^2 + (z_p - z_1)^2 = D_{1p}^2 \]  

(4)

where the leak location \( P = (x_p, y_p, z_p) \), Sensor 1 location \( S_1 = (x_1, y_1, z_1) \), and \( D_{1p} \) the distance between \( P \) and \( S_1 \). The distance \( D_{1p} \) can be expressed as:

\[ D_{1p} = \nu t_{1p} \]  

where \( \nu \) is the velocity of the pressure wave, and \( t_{1p} \) is the traveling time of the P-wave from \( P \) to \( S_1 \).

Equation (4) is a nonlinear equation. It can be expanded to:

\[ D_p^2 - 2x_1 x_p - 2y_1 y_p - 2z_1 z_p = D_{1p}^2 - D_1^2 \]  

(6)

where \( D_p \) and \( D_1 \) are the distances between the mother sensor \( S_0 \) to \( P \) and \( S_1 \), respectively.

While \( t_{1p} \) is unknown, the time difference between the mother sensor and the daughter sensor \( S_1 \), \( \Delta t_1 = (t_p - t_{1p}) \), is known such that

\[ D_{1p} = D_p - \nu \Delta t_1. \]  

(7)
Substituting $D_{1p}$ into Equation (6), we have:

$$x_1 x_p + y_1 y_p + z_1 z_p - \nu \Delta t_1 D_p = \frac{[D_1^2 - (\nu \Delta t_1)^2]}{2}$$  \hspace{1em} (8)$$

From Equation (8) it can be seen that by placing one mother sensor and 4 daughter sensors in the sensor swarm network, the nonlinear equation (4) can be simplified into a linear equation:

$$\begin{bmatrix} x_1 & y_1 & z_1 & -\nu \Delta t_1 \\ x_2 & y_2 & z_2 & -\nu \Delta t_2 \\ x_3 & y_3 & z_3 & -\nu \Delta t_3 \\ x_4 & y_4 & z_4 & -\nu \Delta t_4 \end{bmatrix} \begin{bmatrix} x_p \\ y_p \\ z_p \\ D_p \end{bmatrix} = \begin{bmatrix} \frac{(D_1^2 - (\nu \Delta t_1)^2)}{2} \\ \frac{(D_2^2 - (\nu \Delta t_2)^2)}{2} \\ \frac{(D_3^2 - (\nu \Delta t_3)^2)}{2} \\ \frac{(D_4^2 - (\nu \Delta t_4)^2)}{2} \end{bmatrix}$$  \hspace{1em} (9)$$

where the daughter sensors’ locations $S_i = (x_i, y_i, z_i)$, and the time delay $\Delta t_i, i = 1, 2, 3, 4$, are known.

Define matrix $A$:

$$A = \begin{bmatrix} x_1 & y_1 & z_1 & -\nu \Delta t_1 \\ x_2 & y_2 & z_2 & -\nu \Delta t_2 \\ x_3 & y_3 & z_3 & -\nu \Delta t_3 \\ x_4 & y_4 & z_4 & -\nu \Delta t_4 \end{bmatrix}$$  \hspace{1em} (10)$$

If we assume matrix $A$ is non-singular, the leak point location is obtained directly as follows:

$$\begin{bmatrix} x_p \\ y_p \\ z_p \\ D_p \end{bmatrix} = A^{-1} \begin{bmatrix} \frac{(D_1^2 - (\nu \Delta t_1)^2)}{2} \\ \frac{(D_2^2 - (\nu \Delta t_2)^2)}{2} \\ \frac{(D_3^2 - (\nu \Delta t_3)^2)}{2} \\ \frac{(D_4^2 - (\nu \Delta t_4)^2)}{2} \end{bmatrix}$$  \hspace{1em} (11)$$

where

$$D_i = \sqrt{x_i^2 + y_i^2 + z_i^2}, \hspace{1em} i = 1, 2, 3, 4$$  \hspace{1em} (12)$$

Since the distance $D_p$ is nonlinearly related to the leak point coordinate $(x_p, y_p, z_p)$, further research is needed to optimize the topology of the sensor swarm network so that the $A$ matrix is non-singular and the pinpoint location error is minimized.

This derivation only considers direct propagation of the P-wave from the leak point to the sensors. In a complex space craft cabin, there would likely not be direct propagation, rather multiple reflections of the P-wave off of surrounding walls before reaching the sensors. In such a case, the above equations would need further refinement.
3.3 Leak Repair

Once the Repairbot has arrived at the leak source, RFID tracking confirms leak-point arrival, and Repairbot is sucked into the orifice. It is envisioned that the Repairbot will have small hair-like follicles that are very sensitive to disturbances in the ambient air. Carbon nanotubes, which are finer than human hair, could be used as “feelers” to guide the Repairbot into the leak orifice. As soon as the Repairbot reaches the leak source, glue-foam squeezes out of glue-ports as Repairbot is pushed through the orifice and forms a solid “mushroom-head” plug to seal the leak. The sacrificial Repairbot is entombed within the foam-filled leak eliminating any possibility for causing “new” Space debris. Research is currently being conducted on self-vulcanizing materials for the purpose of leak repair in a pressurized environment. White Sands Testing Facility in cooperation with NASA Johnson Space Center have been testing a leak repair kit called the “Semkit Model 655” which is to be a manually deployed injector-type sealant foam package for repairing leaks in orbit.

Acoustic sensing could also enable detection of minute cracks causing ultra-hypersonic frequencies. In hard to reach Cabin locations, nanotubes with their elastic properties could detach from Repairbot and be carried away by air currents and lodge in the cracks to minimize the rate of air leak until Crew can permanently seal the leak. In a multi-rupture event with more than one leak coordinate illuminated, a swarm of Repairbots are dispatched. In this case each Repairbot is guided by learned fuzzy logic rules that discern the size of leaks by correlating acoustic signals and leak rate. Lithium-Ion batteries can provide all of the necessary power source requirements to the sacrificial Repairbot.

4 Conclusions and Discussion

This paper provides a clear rationale for developing a revolutionary swarm sensing technology to detect leaks in pressurized environments such as the International Space Station and other future environments such as a moon base. Using a bio-inspired swarm of bee-like sensors to automatically repair leaks in orbit, millions or billions of dollars, invaluable time and even human lives will be saved.

Utilizing Swarm Intelligence, this smart group of sensors will be able to locate leaks in a pressurized environment in only a small fraction of the time it takes even the best trained astronaut crew today. In the future, instead of risking their lives trying to find a small leak source in a large moon base, the crew can seek safety in an emergency pressurized zone near evacuation shuttles. Meanwhile the swarm of leak-detecting sensors will have already been released and will be converging on the leak source. Once located, the sensors will begin to repair the fatal breach in the infrastructure. The entire time, humans are safe from danger, waiting for the leak to be prepared and for the pressure to stabilize. Such scenarios and problem-solving systems must be deeply embedded in the future of systems technology and human space exploration. As intelligent systems become smarter, the dividing gap between human and computer potential will continue to disappear.
5 Use of Funds

The Student Fellows Prize Award was roughly utilized as follows:

- $1500 Dell Inspiron 9300 Laptop
- $1000 Dell Inspiron E1700 Laptop
- $1500 Travel Expenses to October Meeting in Boulder, CO
- $1500 Travel Expenses to March Meeting in Atlanta, GA
- $300 for Poster and related media handouts for October Meeting
- $450 Spring Semester Textbooks
- $1750 Spring Semester Tuition
- Remainder for salary and taxes

6 List of Publications and Presentations


- “Dynamic Sensor Net and Sensor Swarm to Locate and Repair Leaks in Pressurized Environments”, PowerPoint handout at the NIAC meeting/poster presentation, Denver, October 2005

- “Dynamic Sensor Net and Sensor Swarm to Locate and Repair Leaks in Pressurized Environments” Poster presentation at the NIAC meeting, October 2005

- “Advancements in the Concept of Sensor Swarms to Repair Pressure Leaks”, NIAC November Status Report, November 2005

- “Micro-robots for repair of atmospheric leaks in CEVs and CLVs caused by impact with Space debris”, JPL/DRDF Proposal submitted by JPL in collaboration with USC, December 2005


- “Revolutionary Technologies for Leak Repair in Space Exploration Vehicles and Space Habitats”, Presented at the NIAC Annual March Meeting, Atlanta, GA, March 2006
7 Acknowledgements

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Appendices
1. **Objective:** A revolutionary concept using micro-robot swarms, Repairbots, to reliably repair leaks caused by impact of CEVs and CLVs with Space debris and micrometeorites in microgravity environments is proposed. The 3-step objective involves: 1. detecting a leak; 2. dispatching a Repairbot to the leak source; and 3. plugging the leak.

2. **Approach:** Cabin piezoelectric pressure sensor network detects a pressure wave caused by the blast of sudden air-leak. Triangulating the wave front time-of-arrivals at the sensors on the Cabin wall surrounding the leak-point, the pressure monitoring system computes the exact leak-coordinates. With Cabin air circulatory systems immediately turned-off to prevent leak growth, leak size is estimated from the change in average Cabin pressure following the pressure transient. Leak size and coordinates are transmitted for repair action to a processor on-board a swarm mother sensor housing several sizes of inflatable Repairbots. Mother’s sensitive membrane-based eardrum sensors independently verify the occurrence of a leak by the delayed arrival of the shock wave front eliminating the possibility of a false alarm by the Cabin pressure monitoring network, and a signal is transmitted to the central alarm system that initiates an emergency safety countdown instructing Crew to don protective goggles. A desired size of Repairbot is selected concurrently by mother’s processor and inflated by air to provide self-propulsion, and a built-in RFID is programmed to the leak coordinates. End of countdown triggers a beam-pointing system to point a Red laser at the leak coordinates. Mother dispatches the Repairbot. A system-on-a-chip processor combines vision, acoustic, and moisture sensing to provide navigation control to Repairbot’s miniature vector-thrust air-jet propulsion system. With narrowband photo detectors providing lock on the laser-illuminated leak coordinates Repairbot navigates aided by hair-like Carbon nanotube clusters that are attracted towards the leak source. At the leak, RFID tracking confirms leak-point arrival, and: 1) Repairbot is sucked into the orifice; 2) Glue-foam squeezes out of glue-ports as Repairbot is pushed through the leak; and 3) a solid “mushroom-head” plug is formed to seal the leak. The expended Repairbot is entombed within the foam-filled leak eliminating any possibility for causing “new” Space debris. Acoustic sensing enables detection of minute cracks causing ultra-hypersonic frequencies. In hard to reach Cabin locations, nanotubes with their elastic properties detach from Repairbot and are carried away by air currents and lodge between cracks to minimize the rate of air leak until Crew can permanently seal the leak. In a multi-rupture event with more than one leak coordinate illuminated, a swarm of Repairbots are dispatched where each Repairbot is guided by learned fuzzy logic rules that discern size of leaks by correlating acoustic signals. Lithium-Ion batteries provide power source requirements to the sacrificial Repairbot. Dispatching Repairbots to a leak source can also be accomplished by employing the Personal Satellite Assistant (PSA), a Micro-Robot developed at NASA/ARC.

3. **Innovation:** The proposed concept has won two national awards - the 2005 NASA Institute for Advanced Concepts Student Prize and the 1st Annual Arthur C. Clark Foundation Astronaut John McLucas Prize for Human Safety in Space, both awarded to Mr. Fronczek for this innovative concept. It presents a simple and reliable way to greatly enhance human safety in space exploration.

4. **Contribution of JPL investigators and external partners:** Collaborating with JPL researcher Dr. Lu are Professor Shen a leading expert in microrobotics of Univ. of Southern California (USC) Polymorphic Robotics Laboratory, and Professor Prasad and Mr. Fronczek from the RioRoboLab, a NASA Ames funded robotics laboratory at New Mexico State University. JPL’s contribution will be towards designing advanced pressure sensor network, and developing system architectures that combine vision, acoustic, and moisture sensing for navigation to the leak-point. Both USC and NMSU external partners will collectively develop a framework for the structural aspects of Repairbots and the systems-level architecture that integrates mechanical, electrical, and autonomous control sub-systems employing advanced fuzzy logic and neural network-based approaches into a reliable leak repair system.

5. **Significant impact on JPL’s technical capabilities:** The proposed concept will greatly enhance JPL’s technology capabilities in the field of highly advanced biologically inspired life support sensors. The DRDF Award will: a) advance the state-of-the-art concept for leak detection and repair and provide enabling technologies for safe Space travel and planetary exploration; and b) enable effective technology integration with programs at NASA/ARC/JSC on human health and safety issues in Space.
Safety in Space Exploration: Revolutionary Technologies to Detect and Repair Atmospheric Leaks in Space Vehicles and Habitats caused by Impact with Space Debris and Micrometeorites\(^1\)

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Abstract

There is a critical need in NASA’s manned Space missions for breakthrough technologies that drastically improve human safety to the highest levels imaginable. Clearly, one of the most significant issues pertaining to human safety is that caused by impact of Space debris and micrometeorites with exploration vehicles and Space habitats resulting in atmospheric decompression. Naturally, any threat to the atmospheric conditions within Space capsules and habitats require instantaneous repair capabilities that minimize risk to the crew and provide sufficient margins for crew to safely evacuate. In this abstract we discuss two revolutionary concepts for automatically detecting and repairing atmospheric leaks in future CEVs, CLVs, and Space habitats that give rise to a bandwidth of new nanoscale sensor technologies.

Without any doubt, upon occurrence of an atmospheric leak a repair mechanism must immediately plug the leak. The simplest and most reliable way to repair is to use a textile-like liner composed of Carbon nanotubes covering the entire inner wall of the Space vehicle or habitat. At the instant of rupture, anything in the close proximity is extruded out of the orifice. “Fluffy” hair-like nanotube clusters close to the wall surface are attracted into the leak source. With their orientation along the axial length of the orifice, the leak source is densely populated by nanotube fibers and therefore has the propensity to plug the leak. Nanotubes have superior elastic properties. The process of extrusion through the leak creates a fiber strand that adds strength and permanence to the repair location.

Carbon nanotubes have excellent electrical characteristics for charge collection and offer the potential for developing highly sensitive acoustic sensors capable of detecting leaks caused by microscopic cracks. The idea therefore is to form a net-like fabric wherein Carbon nanotube clusters act as acoustic sensors. With their close proximity to the inner wall the detection of microscopic cracks is made possible by sensing ultrasonic or even hypersonic frequencies caused by microscopic leaks.

Swarm technology is another approach that adds a layer of redundancy to leak repair. A mother sensor detects leaks, dispatches inflatable Repairbots that self-navigate to the leak source using Carbon nanotube-based acoustic sensors, molecular water detecting sensors, and air current motion sensors, and plugs the leak with the Repairbot entombed within the leak. While these sensors provide a basis for sensing key environmental effects within the Space containment during atmospheric decompression, they have a multitude of other uses in planetary exploration.

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