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ABSTRACT

The behaviour of fluids in microgravity imposes a risk to an Extravehicular Activity (EVA) crewmember. The intrusion of water into air conduits used for pressurization and breathing would flow with minimum resistance in the direction of pressure differential. Such an intrusion would cause water to enter into the helmet breathing space and could cause suffocation and drowning in addition to loss of vision and loss of communication. It is hence prudent to detect this water intrusion before it accumulates undetected to a dangerous level.

This paper offers a design to address this risk. A sensor system is described that detects the water intrusion into the air lines that are part of the Extravehicular Mobility Unit (EMU) life support system. Upon detection, the EVA can be terminated before a harmful state is reached.

1. INTRODUCTION

Extravehicular Activity or EVA is one of the most hazardous and also indispensable aspects of human spaceflight. EVA’s have enabled feats like construction and maintenance of the International Space Station and the Hubble repair mission. The safe execution of an EVA with minimal compromise on functionalities is hence a prime motive.

On 16th of July 2013, astronauts Luca Parmitano and Christopher Cassidy began Extravehicular Activity 23 aboard the International Space Station. About 44 minutes into the EVA, Parmitano reported water at the back of his helmet which slowly migrated to the front of his face. The EVA was terminated and Parmitano struggled to make it back to the airlock, having vision out of the visor impaired and breathing with the suspended water arduous. He also had audio communication issues due to the water in the helmet interfering with the communication system. However, he relied on tactile feel of his safety tether and ingress into the airlock. Both he and Cassidy were re-pressurized. It was found that about 1.4 litres of water had accumulated inside the helmet. The mishap investigation board labelled this incident as a “High Visibility Close Call”. The astronaut was determined to have been exposed to potential loss of life due to drowning [1].

The sensor system described in this paper mitigates the consequences of the failure, which is water intrusion into air lines. This is done by detecting the presence of water, and upon exceeding a particular quantity limit, a warning is issued. This warning may lead to an EVA termination. The water detection would enable termination of the EVA and a safe re-pressurization before the water buildup becomes hazardous.

The system introduced is an initial concept. Further Research & Development and testing is needed in order to address practical issues (like proper calibration of sensors considering the innocuous presence of moisture due to breathing, and perspiration due to physical activity) in implementing it to Extravehicular Activity space suits.

2. THE EXTRA VEHICULAR MOBILITY UNIT

The Extravehicular Mobility Unit or the EMU is a self-containing life support system for astronauts performing spacewalks outside the protection of the spacecraft environment in low earth orbit [2]. Following is a brief description of the EMU parts relevant to this paper. An overview of the different parts of the EMU are presented in Fig. 1.

The EMU consists of two main components:

- The pressure garment or the Space Suit Assembly (SSA) which provides pressurized envelope, mobility and thermal control.
- The Primary Life Support System (PLSS) with a Secondary Oxygen Pack (SOP) which provides life support, power and communication systems.

The PLSS comprises of four main circuits:

- Oxygen Ventilation Circuit
- Primary Oxygen Circuit
- Feedwater Circuit
- Liquid Transport Circuit

The Primary Oxygen Circuit provides oxygen at regulated pressure to the Oxygen Ventilation Circuit which the astronaut uses for breathing. It is also used for pressurizing the Space Suit Assembly, aiding in water expulsion from the water tanks on PLSS and its pressurization. The exhaled Carbon Dioxide goes through a METOX canister where it is removed and dumped overboard. A fan-pump-separator system is used to both circulate the
exhaled air through the air processing components and to partially remove the water vapor in air. The remaining humidity removal and oxygen cooling occurs in the sublimator. The water collected is directed back to the water storage tanks. Water storage tanks are part of the Feedwater Circuit, so is the sublimator. The water storage tanks supply water to the Liquid Cooling and Ventilation Garment (LCVG) which is a garment worn inside the EMU, lined with cooling water tubes and is part of the Liquid Transport Circuit. This is used to remove body heat produced during the EVA operations and is re-cooled in the sublimator. The water storage tanks also supply expendable water to the sublimator, where after collecting heat, is dumped overboard as it freezes.

The Secondary Oxygen Pack provides 30 minutes of backup oxygen supply. This could be initiated either if the primary supply is exhausted, the primary regulator fails or if one of the purge valves (purge to space) is opened.

Other components of the PLSS/SOP assembly are the space-to-space radio, Enhanced Caution and Warning System (ECWS) and the Display and Control Module (DCM). ECWS monitors the system operational conditions and the DCM allows the crewmember to control them.

The two parts (SSA and PLSS/SOP) are covered by the Thermal Micrometeoroid Garment (TMG).

3. CAUSE OF EVA 23 MISHAP

After a thorough investigation, it was determined that the fault most likely lied in the water separator circuit. The filter just upstream to the water separator unit was found to be clogged with inorganic impurities. Obstruction of this filter prevented adequate flow through to the unit. This in turn prevented the pitot pump from circulating all of the flow coming in from the gas trap. The excess water then flooded the water separator drum and entered the ventilation loop at the fan inlet. The source of the impurities is as yet unknown [2].

4. PROPOSED SENSOR TO MITIGATE THE RISK

The schematic of the sensor system is shown in Fig. 3. The basic concept used is the absorption of light energy by the leaked water droplets. Two sections of the air conducting pipe have a sensor assembly in between them, joined by pneumatic fittings. The portion of the pipe in the sensor assembly is transparent in order to allow light energy to be transmitted. On one side of sensor, an Infrared (IR) light source is placed. The light generated by this source travels through the pipe diametrically and falls on a photodiode. The photodiode generates a nominal current as long as the obstruction to the IR light is sufficiently low. It is calibrated for this nominal operation, taking into account the absorptive coefficient of the transparent pipe, full range of air flow rates, directivity effects of the IR emitter and receiver and moisture expelled from the body.

In the event of a fluid leak into the air pipe, the water droplets (suspended due to microgravity) pass between the IR source and the photodiode. Absorption of the light energy by the water causes the intensity of light falling on the photodiode to drop beyond the set limit. This in turn causes a drop in current output which activates a warning system, part of the ECWS.
A cross-sectional view of such a setup is shown in Fig. 4. As shown, the setup may be enclosed in a rectangular frame with two opposite sides fixed and supported to the EMU. This prevents relative motion between the sensor and the pipe. One side of the frame may be removable to make assembling and disassembling easier. There may be a cover along the cross section to prevent outside light from affecting the detector reading.

![Figure 4. Cross sectional view of the sensor system](image)

There may be several of such sensors placed at various points in the air circuit. This achieves two objectives. One, there may be several sources of water intrusion into the pipe and having the sensors downstream of the possible locations maximizes the probability of detecting the water presence. Second, having more than one sensor makes it possible to confirm the warning generated by the first sensor. As the water is carried by the air flow, it activates successive sensors with a certain time delay. This asserts the presence of water. The concept is illustrated in Fig. 5.

![Figure 5. Multiple sensors placed along the air conduit to form a more robust system](image)

5. CALCULATING THE DETECTOR REQUIREMENTS

An equation is derived that relates the fractional reduction in intensity of IR light detected to the size of water droplet, the size of the sensor and the absorption coefficient of water at the IR wavelength. This aids in selection of the sensor based on the maximum allowable water quantity passing through the sensor.

\[
\Delta I / I_o = (4/3) \times (\mu R^3 / S^2)
\]  

\( I_o \) is the intensity of IR light emanating from the IR LED (Light Emitting Diode), \( \Delta I \) is the drop in intensity detected at the photodiode, \( \mu \) is the absorption coefficient of water at the IR wavelength, \( R \) is the maximum allowable radius of water droplet passing through and \( S \) is the diameter of received light on the photodiode. The variables are illustrated in Fig. 6.

![Figure 6. Illustration of detector radius and droplet radius](image)

Assume the following:

\( \mu = 10 \text{ m}^{-1} \) (for IR source wavelength of 940 nm)
\( S = 0.01 \text{ m} \)
\( R = 0.005 \text{ m} \)

Plugging these numbers into Eq.1, the fractional drop in intensity, \( \Delta I / I_o \) obtained is 1.667%.

With the given requirement for droplet size detection, the pipe size and the IR source wavelength, the detector needs to detect a drop in intensity of 1.667% and higher which is also the minimum resolution required. This also means that the error in the detector must be less than half of this value, i.e. 0.833% of the nominal intensity value.

6. SIGNAL PROCESSING

This section describes how the output from the detector is processed and how a warning to ECWS is issued in the event of a fluid breach.

The output from the photodiode is first sent into the bandpass filter, centred at an output frequency with a certain bandwidth. Signal noise is removed at the bandpass filter. It is then sent to the power amplifier, which makes it easier for the filtered signal to be further processed by increasing its power. The analog to digital converter then converts this analog signal to a digital signal so that it can be used in the microcontroller. The microcontroller then verifies if the signal current is less than current for nominal operation by a certain tolerance value. If the signal current is less than the nominal current by a certain value, corresponding to the minimum intensity drop calculated above, another signal is generated which is the warning signal. This warning signal goes to:
1. The communication cap earpiece where the warning signal is converted to a sound of required characteristics.

2. A light display on the Display and Control Module (DCM) on the EMU.

3. Space to Space Antenna where the signal is sent to the ISS crew and onward to the Mission Control Center.

This processing is done for each sensor output.

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7. OVERVIEW OF SYSTEM SPECIFICATIONS

The major components of the sensor system are the IR LED and the photodiode.

7.1. Infrared LED

It can be seen in Fig. 8 that the absorption coefficient for water is higher in the near infrared region than in the visible region. This is preferable because higher degree of absorption leads to a greater drop in intensity measured at the detector and makes it possible to detect smaller droplets with greater accuracy. The wavelength of the light used in Eq. 1 falls in this region.

7.2. Photodiode

The photodiode chosen needs to work in the bandwidth of the IR LED described above. This is shown in Fig. 9 which corresponds to a wavelength of 940 nm used in Eq. 1. The output frequency of the sensor is 30 kHz [4]. The output signal must be filtered for frequencies around the output frequency with necessary bandwidth in order to remove noise. As such, noise due to ambient light is expected to be negligible due to the fact that this system is inside the Space Suit Assembly and the detector only receives light from the IR source.

7.3. Overall weight and power requirements

A total number of five sensor systems is assumed to be required in the EMU considering the total length of the air conduits and the possible water intrusion points. A sensor system includes: the IR LED, photodiode, band-pass filter, power amplifier, analog to digital converter and microcontroller. The total power requirement for the five systems is estimated to be less than 600 mW, the total mass less than 700 g, volume for IR LED and photodiode 10 cm$^3$ and volume of the remaining components 60 cm$^3$.

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8. CALIBRATION OF THE SENSOR SYSTEM

As mentioned, the sensor system shall be calibrated for a nominal operation, taking into account the absorptive coefficient of the transparent pipe, the full range of air flow rates and the directivity effects. Another factor that should be taken into account in calibrating the sensor is the moisture present in the nominal air flow.
A substantial amount of moisture may be present as a result of the breathing process and perspiration from the crew member (due to strenuous activity). This moisture present in the air conduits needs to be accounted for while measuring the presence of leaked water. Not doing so would lead to an over estimation of the leaked water presence and generate a faulty warning. The calibration of the sensors for nominal operation must hence take into account the full range of moisture presence as well, which dictates the limit on water permissible in the air lines. Optimally, the sensors upstream of water separator may have a higher tolerance for water and sensors downstream, a lower tolerance.

Further tests need to be carried out in order to determine if the calibration of the sensor is sufficient to account for this presence of moisture. Design changes may be made accordingly.

9. TEST PROGRAM

The capability and proof of concept shall first be done on ground using the sensor system as detailed in the preceding sections. Due to the presence of gravity, the water would not take a spherical form. To counter this problem, a spherical thin hollow glass shell (of known absorption coefficient) can be filled with water and introduced into the sensor system. The response of the sensor can be observed and the sensor can be validated. This operation is shown in Fig. 10. Once the sensor has been demonstrated on the ground, it can then be flown to the ISS for the system qualification.

![Figure 10. Illustration of testing the sensor system on ground](image)

If the sensor system concept clears all other qualification tests (as the case may be for each electronic component as per the necessary guidelines) and is to be installed on the existing EMU’s, during the checkout of an EMU prior to launching it to the ISS, the sensors shall undergo the ground testing and calibration (for each sensor to follow the same requirement for maximum allowable intensity drop) described above. The installation of the sensor system on the suits will require replacing the existing ventilation line with several smaller ones in order to accommodate the sensors and joined by pneumatic fittings, as shown in Fig. 3.

10. OTHER APPLICATIONS OF THIS SENSOR CONCEPT

The concept discussed in this paper can be extended to other applications as well. One example is to use a spectrometer (in place of the photodiode) and a light source of applicable wavelength(s) in order to detect the presence of certain gases or liquids like Carbon Dioxide. This would detect the presence of these molecules by analysing their absorption spectrum. A similar approach to detect water, fluids or gases can be used in fluid lines which form part of the Environmental Control and Life Support Systems of a manned spacecraft or space station.

11. SUMMARY

A high risk operation like the EVA needs the safest possible systems. The sensor concept detailed in this paper acts as a safety feature that detects the presence of leaked water in air lines in an Extravehicular Activity space suit, preventing the failure mode from being catastrophic. This design accomplishes that goal at very little additional cost, weight and lead time.

12. REFERENCES

The 8th IAASS International Space Safety Conference “Safety First, Safety for All”, will be held in Melbourne - Florida (USA) in the period 18-20 May 2016. The IAASS conference is the premiere international forum dedicated to the discussion of a wide variety of space safety topics.

The conference offers a unique opportunity to meet top U.S. and international experts in space safety and related engineering fields, from industry, academia and agencies. An occasion for exchanging views and establishing new professional bonds, towards the common goal of forging and a global space safety culture.

The online registration is open. You can access the online registration form at http://iaassconference2016.space-safety.org/registration/ or directly by clicking the red tab at the bottom of this page. Early Birds registration ends 14 March 2016.

**TIMETABLE OF CONFERENCE EVENTS**

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At the occasion of the Conference Gala Dinner on May 19, 2016 the IAASS will assign three awards:

- Jerome Lederer Space Safety Pioneer Award
- Vladimir Syromyatnikov Safety-by-Design Award
- Joseph Loftus Space Sustainability Award

These prestigious awards are a means to honor and recognize safety professionals and systems designers and engineers who have made outstanding contributions towards space safety.
Progress in space safety lies in the acceptance of safety design and engineering as an integral part of the design and implementation process for new space systems. Safety must be seen as the principle design driver of utmost importance from the outset of the design process, which is only achieved through a culture change that moves all stakeholders toward front-end loaded safety concepts. Superb quality information for engineers, programme managers, suppliers and aerospace technologists.