A NOVEL METHOD FOR PREDICTION AND WARNING FOR UNCONTROLLED RE-ENTRY OBJECT IMPACT

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ABSTRACT

The growing Micrometeoroid and Orbital Debris (MMOD) environment in Earth orbit poses an increasing risk not only to active satellites but also to the general public. Of particular concern are the objects in low earth orbit (LEO) which have the potential for catastrophic consequence upon entry and collision with vulnerable terrestrial targets including airborne planes. There are limitations to the ability to predict uncontrolled object re-entry with sufficient precision to give timely or actionable warnings to threatened air traffic zones or surface locations. A system called R-DBAS (Re-entry Direct Broadcasting Alert System) invented by the co-author of this paper, T. Sgobba former head of the European Space Agency Independent Safety Office, has the potential to avoid catastrophic impacts by generating timely surface or air traffic impact warnings. The system includes a self-contained housing with on-board geolocation receiver, processing, memory with debris breakup models, and direct warning broadcast capability.

1. ORBITAL DEBRIS IN CONTEXT

The increased utilization of near-Earth space has resulted in a growing accumulated MMOD environment [1]. To mitigate risk from space debris, all spacecraft need to address the risk associated with potential impact through design and operational controls. For human space exploration and many unmanned programs, the risk to MMOD can be a significant risk driver [2]. The public has become more aware of this growing threat as evidenced by the 2013 feature film *Gravity* [3].

Broadly, there are three size categories of MMOD objects in near-Earth space. The smallest particles are those smaller than a few millimetres (<1 cm) in diameter that are too small to be individually tracked by optical, infrared, or radar methods [4]. Generally, these articles do not contain sufficient mass and energy to pose collision damage. Cumulative impact can create a hazard depending upon the respective location and application on a space vehicle.

Intermediate size MMOD objects (~1-10 cm) can pose a catastrophic hazard for on-orbit collisions but are too small to be tracked by remote sensing methods. As such, a space vehicle cannot rely on orbital conjunction avoidance manoeuvres to mitigate the hazard. Risk is mitigated by shielding particularly vulnerable spacecraft locations.

Analysts model risk using tools such as the National Aeronautics and Space Administration (NASA) Orbital Debris Engineering Model (ORDEM) [5] and the European Space Agency (ESA) Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) [6] which quantify the particle density as a function of particle size for the corresponding orbit (altitude, inclination, etc.).

The largest MMOD objects are those which can be tracked and include complete spacecraft or spent upper stages (>10 cm). A collision with one these large objects would be catastrophic and avoiding impact is the only option. These objects can be tracked by optical, infrared, or radar techniques and their orbital locations propagated forward in time. Potential orbit conjunctions with spacecraft that are still under active control can be prevented through notifying spacecraft operators.

2. POST MISSION SAFETY THREAT

Mitigating the effect of orbital debris has strictly been the domain of space vehicle operators. Space debris in Low Earth Orbit (LEO) has been considered essentially an orbital environmental issue critical for maintaining the benefits afforded by space access. However, in recent years, awareness of dangers arising upon random re-entry has started to emerge. With the projected proliferation of satellites, it is necessary to consider and protect against the risk to the general public.

About one hundred large space systems (satellites or rocket upper stages) re-enter the Earth's atmosphere annually. In the coming years, the number of operating satellites in Low Earth Orbits (i.e. between 160 km and 2000 km) may increase exponentially and, in addition, they will have shorter operational lifetime, thus requiring frequent replacements. As of January 2015 there are 669 satellites operating in Low Earth Orbit, but there are recent applications filed with ITU (International Telecommunication Union) in Geneva for launching about 11,000 satellites (the so-called space-based internet goldrush) including mega constellations of 4,000 satellites each or more like those planned by SpaceX (USA) and STEAM-1 (Norway). Including the additional rocket upper stages that will be left in orbit after launching these satellites, atmospheric re-entries will become in future a multiple daily occurrence.

For many years, man-made objects re-entering the Earth's atmosphere have not been viewed as a hazard because the heat generated during re-entry was expected to completely destroy them and the statistical likelihood of a collision was considered small. Only very large space structures like Skylab and MIR station or satellites containing radioactive or other toxic materials were deemed significant threats. Many satellites and rocket upper stages re-enter the Earth's atmosphere, but only a limited number of pieces have been reported and actually recovered [7, 8, 9, 10].

This may be a consequence of the low probability of impacting a populated area on the Earth's surface and then found. When detailed searches for debris were done on a large scale, as was the case following the Space Shuttle *Columbia* accident, the amount of recovered debris greatly exceeded expectations.

It is commonly assumed that 10 to 40% of the pre-reentry dry mass of the space system survives as fragments that are large enough to be hazardous to the public on ground. Some limited studies conducted in the USA have quantified the annual risk for aviation due to random re-entry in the order of 3×10^{-4} that *"... is above the long term acceptable risk for a flight exposed to such a risk, but below the short term acceptable risk based on risk acceptability guidelines used by the FAA for other types of threats*" [11]. Surviving small fragments are not considered in this estimation.

Small fragments that are non-hazardous for people on the ground because of low kinetic energy at impact and/or because of sheltering provided by buildings, houses, cars, etc., are potentially hazardous for aircraft due to relative velocity at impact, and because of aircraft structures and systems vulnerability. A fragment of 300 grams is considered by USAF norms catastrophic for an airliner [12].

3. UNCONTROLLED DEBRIS RE-ENTRY

Controlled re-entries of large orbital objects are not significant risks to potential air or ground targets when those objects are brought down over uninhabited and unused portions of the Earth. Areas of the South Pacific Ocean are often used as final deorbit targets [13].

Uncontrolled re-entry is particularly complex and difficult to predict. The breakup and trajectory are stochastic and depend on the object's physical characteristics, orbital elements and environment including the perturbing gravitational influences, exosphere state, and space weather characteristics. During the final stages of a debris object's orbital life, the perturbations from atmospheric drag may equal or exceed any gravitational perturbations [14]. Uncertainty in the dominant perturbing force induces significant uncertainties in any re-entry path prediction.

There is a finite number of operational debris tracking systems [4]. The utility of each system is constrained by its location and respective field of view, and (for optical or near infrared systems) lighting constraints. There is substantial error in developing any given object's state vector given the limited ability to track an object at stations around the globe.

The uncertainties in determining these parameters preclude determination of re-entry in a manner to notify the public to take corrective action. As an example, consider the launch failure of the Progress-M 27M mission to resupply the ISS on April 28, 2015. The Center for Orbital and Re-entry Debris Studies predicted the subsequent reentry several days later with a ±2 hour window [15]. The corresponding predicted re-entry location spanned nearly three orbits. This uncertainty precludes generating and issuing actionable warning to air traffic or ground locations.

Predictions for the Mir space station re-entry were similarly broad when it was actively de-orbited in March, 2001 [16]. The final predicted area of impact was ±2500 km by ±100 km. A new approach to re-entry tracking is needed in order to improve impact time and location predictions to the level of being such that the advanced warning is actionable by aviators and ground persons.

4. SELF-MONITORED DEBRIS RE-ENTRY

In this paper, a new approach to protecting the public from re-entry objects is proposed [17]. This system significantly reduces the inherent uncertainties in remote sensor-based re-entry prediction and warnings. The reentering object can be considered self-monitoring under this proposed method.