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OBJECT ORIENTED STUDIES INTO ARTIFICIAL SPACE DEBRIS

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ABSTRACT

A prototype simulation is being developed under contract to the Royal Aerospace Establishment (RAE), Farnborough, England, to assist in the discrimination of artificial space objects/debris.

The methodology undertaken has been to link Object Oriented programming,intelligent knowledge based system (IKBS) techniques and advanced computer technology with numeric analysis to provide a graphical, symbolic simulation. The objective is to provide an additional layer of understanding on top of conventional classification methods.

Use is being made of object and rule based knowledge representation, multiple reasoning, truth maintenance and uncertainty. Software tools being used include Knowledge Engineering Environment (KEE) and SymTactics for knowledge representation. Hooks are being developed within the SymTactics framework to incorporate mathematical models describing orbital motion and fragmentation. Penetration and structural analysis can also be incorporated.

SymTactics [15] is an Object Oriented discrete event simulation tool built as a domain specific extension to the KEE environment. The tool provides facilities for building, debugging and monitoring dynamic (military) simulations.

INTRODUCTION

There are currently some 10,000 registered objects orbiting the Earth. It is estimated that another 40,000 golf-sized objects are not tracked along with billions of still smaller pieces. These objects consist of satellites, extinct rocket casings and debris.

Space debris can be effectively categorised under the headings of : particles, fragments and artifacts [10].

Many tiny particles are produced by solid rocket motors used in space. Larger particles can be attributed to the intense thermal cycling of the space environment (for example paint flaking off satellites). Particles are likewise produced by explosions, both accidental and deliberate.

A principle source of fragments and particles is the destruction of spent rocket stages and satellites. Explosions of rocket stages can occur many months or years after launch. Residual propellants may be the cause here. Spacecraft on the other hand tend to be destroyed deliberately. This may result from testing anti-satellite weapons, or spacecraft being commanded to self-destruct for various reasons.

Numerous parts of spacecraft are jettisoned during launch and operation; these come under the fragment category. Fragments of this type include interstage structures, payload shrouds and support structures. Fragments are likewise produced during rocket stage separations.

The term artifacts is applied to derelict items of space hardware such as intact payload support structures, spent upperstages and spacecraft. Spacecraft can become derelict (non-operational) following the malfunction of a launch vehicle/upper stage, insertion into an incorrect orbit or following a system malfunction.

A major concern exists that space debris may cause collisions, particularly in orbits ranging from 500km to 1100km above the Earth. These collisions can produce many small fragments which in turn increase the probability of further collisions.

Space scientists and mission planners are becoming increasingly concerned about the possibility of space objects (namely spacecraft, rockets, spaceplanes and space stations) being damaged by artificial space debris. Similar problems exist, though not to the same extent, when placing telecommunication satellites into geostationary orbit.

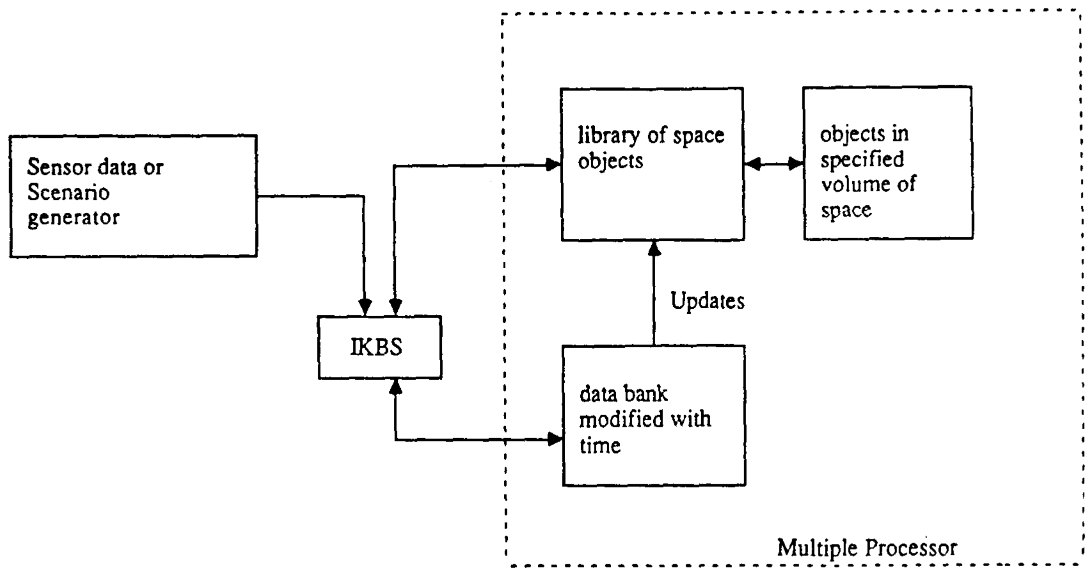
Should an operational space object become non-operational, it is in the interest of space scientists and mission planners to determine the cause of this event as soon as possible. If space debris is suspected, the resultant signature data and detailed simulations could identify the nature and cause of this event.

SYSTEM CONFIGURATION

The proposed system configuration for this simulation (see Fig. 1) makes use of a library of space objects, intelligent sensors and a scenario generator. When a sensor detects an object, it interrogates the library of space objects to determine if that object has been identified/categorized. If not, the sensor reasons as to the possible cause and origin of the unidentified object.

The first phase of this prototype simulation is currently being modelled on a Lisp machine. The computer used was a Symbolics 3640. The simulation is now in the process of being

Figure 1: System Configuration



transferred to a microVAX workstation in order to test the concept of the "High Performance Server" [1,2]. The idea of this concept is to enhance the host computer with add-on extensions. These extensions would be modular, based on a combination of any relevant architecture, and would produce a fast, high availability processor system for symbolic, numeric, graphic and conventional processing.

CURRENT WORK

The current phase of work includes orbital dynamics, fragmentation, object representation and sensor reasoning.

ORBITAL DYNAMICS

Calculations are being undertaken to assess the outcome of imparted impulses (ΔV's) to objects, fragments following explosions, collisions and hypervelocity impacts.

Modelling discrepancies were minimised by transfering from orbital elements (simple Keplerian motion) to cartesian co-ordinates [3,5,6] at the time a simulated event had been scheduled to take place. Resultant new velocities following fragementation were used to calculate individual debris/particle orbital elements.

An assumption was made that an operational space object described an unperturbed circular orbit. Following fragmentation, it was observed that the majority of resultant particles described elliptic motion; some achieved escape velocity. Simulations showed that the small particles ($<$ 0.1gm) can have drastically different orbits from the initial parent body orbit. They had either very noticeable differences in orbital inclination and longitude of ascending node or large variations in semi-major axis and eccentricity. Resultant debris envelopes should correspond to those described by Fuss [4,7].

FRAGMENTATION

The number of fragments generated and fragment velocities following hypervelocity impacts and explosions were based on work by McKnight [11], Su & Kessler [14], and studies undertaken in the 1960's. The following assumptions were made in simulating fragmentation:

(i) Mass distribution of debris resulting from hypervelocity impact is a function of impact velocity and mass of projectile [9,11,14]
The ejecta mass is represented by

$$M_e = v^2 M_p$$

where M_e = ejecta mass in grams
v = impact velocity, km/sec
M_p = mass of projectile in grams

(ii) The ejecta mass distribution takes the form [9,11]

$$N = 0.447 (m/M_e)**(-0.7496)$$

where N = number of fragments with mass m or greater
m = fragment mass
M_e = total ejecta mass

(iii) The general equations for debris resulting from the explosion of a satellite are [11,14]

$$N = \begin{cases} 1.71E\text{-}4\ M_t \exp(-0.02056\ m **0.5)\ ;\ m > 1936gm \\ 8.69E\text{-}4\ M_t \exp(-0.05756\ m **0.5)\ ;\ m < 1936gm \end{cases}$$

where N = cumulative number of fragments with mass greater than m grams
M_t = mass of target object in grams

(iv) The smallest detectable ejecta mass is of order 0.1gm

(v) The ejecta velocity for the smallest detectable fragment is 1.3 times impact velocity [9]. Velocities of larger ejecta particles were computed on the assumption that the kinetic energy was the same for all ejecta particles.

(vi) The maximum ΔV's imparted to fragments following an explosion are of order 2km/sec. Larger fragment velocities were calculated on the assumption that the kinetic energy was the same for all particles.

Initial results suggest that particle distributions could be detected showing the equivalent of a double shock wave following a hypervelocity impact and resultant explosion. Particle and velocity distributions may likewise indicate the orbital plane and velocity of the impacting body.

OBJECT REPRESENTATION

An object oriented approach was used to describe space object characteristics and relationships in terms of its attributes; namely instance variables and methods. Instance variables describe the simple variables or object relations that an object may possess; methods are operations that the object may perform.

A class of generic objects, termed operational component parts, was used to represent all functional/operational space objects such as satellites, rockets, spaceplanes and space stations. A sub-class of operational component parts was used to describe a typical space object. Terminology such as "forward-of", "behind", "above", "bottom", "left-of", "right-of" and "enclosed-by" was then introduced to represent spacially the component parts of the space object. In addition, each operational component part had assigned attribute fields describing mass, shape, material and structural properties. This is akin to the approach taken by such products as ICAD [13].

As an example consider the objects fuel tank, oxidiser tank, helium tank and rocket engines. These are a generic sub-group of operational component parts which can be used to represent the Space Shuttle's orbital maneouvering system [12]. These component parts could likewise represent the orbital control system for a space station or satellite.

Geometric reasoning was introduced to generate more accurate fragmentation models following impacts and explosions. The model assumed that debris was equally reflected and transmitted when the outer skin of a space object had been penetrated by an impacting body. It was further assumed that the transmitted debris damaged an operational component part causing the part to move into the class of non-operational objects. The model used rules to assess whether the damaged part was critical or non-critical; the outcome of this assessment resulted in debris being generated according to equations describing explosions or impacts respectively. Additional fracture and penetration models could be incorporated at this stage for more detailed simulations.

When a component part became non-operational following an impact or explosion, messages were passed to surrounding components to evaluate the outcome of this event. The outcome could be further explosions, shattering, fragmentation or fracture, resulting in adjacent components likewise moving into the class of non-operational objects.

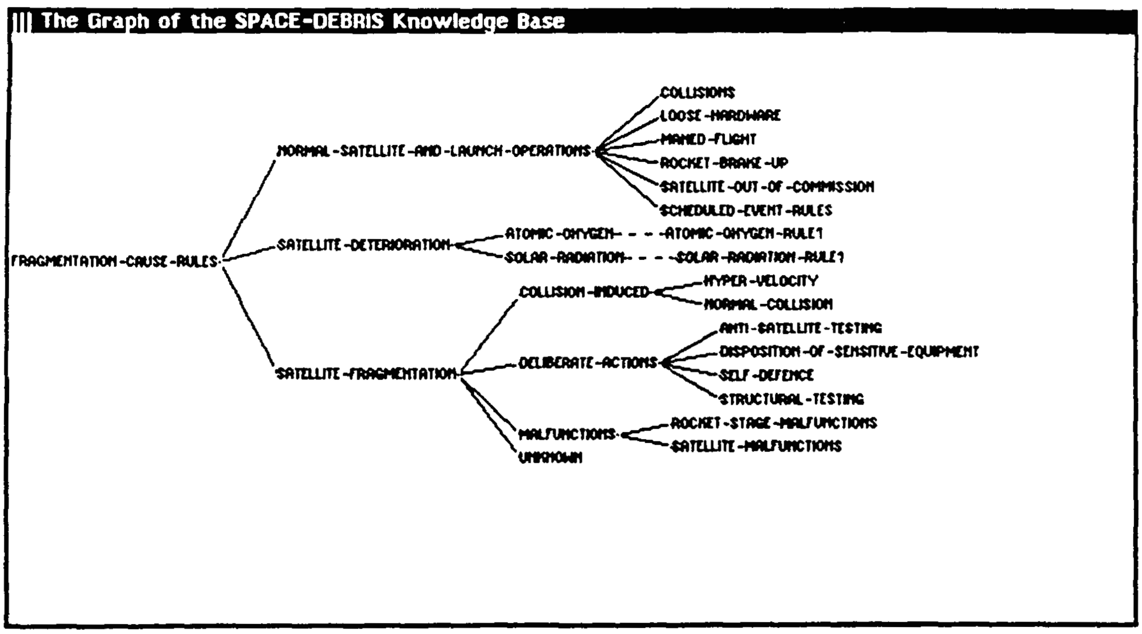
SENSOR REASONING

This was modelled as an intelligent system having inputs from various types of sensors and access to a library of currently known space objects. Consider the following scenario:

A possible cause for the loss of communication with a space object could be due to a collision, explosion or hypervelocity impact; this type of event being termed as a "non-scheduled event". The affected object or component parts of the affected object would transfer from the class of operational objects to non-operational objects. The sensor, having detected non-catalogued debris, would use fragmentation-cause-rules to determine the nature and origin of the detected debris, using as a key the time and known position of the suspected space object.

Fragmentation-cause-rules were classed under normal satellite-and-launch-operations, satellite-deterioration and satellite-fragmentation [8]. These were further categorized (see Fig 2) under collisions, loose-hardware, manned-flight, rocket-break-up, satellite-out-of-commission, scheduled-events, atomic-oxygen, solar-radiation, collision-induced, deliberate-action, malfunction and unknown.

Fig. 2



When non-catalogued debris was detected, the sensor reasoned as to the possible cause and origin. In undertaking this task, the sensor had access to an event library of non-scheduled and scheduled events. A non-scheduled event, as described earlier, could be a sudden loss in communication with an operational satellite. A scheduled event could be a hard-eject fragment following payload deployment into orbit. In this case, the following fragmentation-cause-rule was used to test this hypothesis:

```
HARD-EJECT-FRAGMENT
------------------------------------
((IF (THE EVENT-TALLY OF ?DEBRIS IS ?EVENT)
     (?EVENT IS IN CLASS HARD-EJECT)
     (THE ACQUIRED-OBJECTS OF ?OBSERVATORY IS ?SIGHTING)
     (?DEBRIS = (LISP (FIRST ?SIGHTING)))
     (THE CATALOGUE OF ?OBSERVATORY IS ?CATALOGUE)
     (?FRAGMENT-CAUSE = (FOURTH ?CATALOGUE))
     (LISP (= ?EVENT ?FRAGMENT-CAUSE))
     (?RCS = (LISP (SECOND ?SIGHTING)))
     (?RANGE = (LISP (THIRD ?SIGHTING)))
     (LISP
      (< ?RCS
         (OBJECT-MESSAGE 'NORMAL-ATMOSPHERE
                         '!ATTENUATE-SIGNATURE
                         '!RADAR-SIGNATURE
                         1.0e-4
                         ?RANGE
                         'KM)))
    THEN
     (THE DEBRIS-ORIGIN OF ?DEBRIS IS ?EVENT)
     (THE IDENTITY OF ?DEBRIS IS SMALL-FRAGMENT)))
```

If several fragmentation-cause-rules offered plausible solutions, each one could be tested concurrently. A possible confirmation of a rival hypothesis could be obtained by calculating orbital parameters at the time of the scheduled event and comparing the data with available fragmentation models.

CONCLUSIONS

The outcome of this study to date has shown that deep knowledge based simulations requiring symbolic, numeric and visualisation techniques could be linked together and applied to the artificial-debris problem. The use of KEE and SymTactics enabled rapid prototyping and provided an interactive and rapid scenario generation facility.

It is hoped that the outcome of this study will provide a better understanding of:

i) Object representation, damage assessment
ii) Intelligent sensor representation
iii) Object classification, discrimination and hazard/lethality.
iv) Generation of various space debris scenarios to provide a better understanding of the cause and break-up of operational space objects.

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