DEVELOPMENT OF HARPOON SYSTEM FOR CAPTURING SPACE DEBRIS

Jaime Reed[(1)], Simon Barraclough[(1)]

[(1)] *Astrium Ltd., Gunnels Wood Road, Stevenage, SG1 2AS, UK, Email: Jaime.Reed@astrium.eads.net*

ABSTRACT

Active removal of large space debris has been identified as a key activity to control the growth in the debris population and to limit the risk to active satellites. Astrium is developing technologies to enable such a mission, including a harpoon capture system.

The harpoon is simple, compact and lightweight. Since the capture is fast (typically <0.5s) it is relatively insensitive to the dynamic state of the target and orbital dynamics, simplifying the mission design.

The harpoon system is designed to attach to the target whilst also minimising damage. The harpoon consists of a set of barbs to robustly hold the target, a crushable section to absorb excess impact energy, and a tether to connect to the chaser vehicle. The baseline firing system uses compressed gas, although a simpler one-shot system has also been designed.

To understand how a harpoon could be applicable to active debris removal an on-ground prototype and test-rig has been developed for trials with real structural elements of satellites and rocket bodies. Testing has demonstrated the feasibility of the concept and this paper describes the results as well as the next steps. A number of design variants are also proposed which could simplify the system design of an ADR mission.

1 INTRODUCTION

Around 5900 tons of space debris are estimated to be orbiting the Earth [1], including dead satellites, rocket upper stages and lost equipment. They represent a hazard to any operational spacecraft, as collisions with debris can seriously impair their performance or, in the extreme, render them inoperative. Each collision also creates more debris, increasing the probability of further collisions [1,2]. To permit reliable access to space in the future 3 measures can be envisaged:

1. Reduce vulnerability to small debris, i.e. the millions of untracked (<1cm) items
2. Avoid generating new debris in future missions
3. Prevent future collisions by collision avoidance manoeuvres and removing existing debris

Even implementing 90% successful post-mission disposal (PMD) the number of objects will still increase [1] and therefore it could be necessary to envisage the removal of existing objects, as well as develop the capability to remove future objects which fail to perform a successful PMD.

NASA and ESA studies [1,2] have demonstrated that removing the large debris objects which act as ‘reservoirs’ has the biggest effect on the debris population. Typically these are either satellites which have failed or ended their missions, or upper stages from past launches. However each target is individual, with a wide range of shapes, sizes and configurations. Therefore it is necessary to consider a variety of different solutions. To support this work Astrium has been developing a number of complementary technologies which could be useful in this endeavour:

- Robotic arm capture as part of the DLR funded DEOS project, building on Europe’s extensive expertise in this area [2]
- A net capture system which has been extensively demonstrated in zero-g [4]
- A harpoon system [4], described here, which has been extensively tested on the ground
- Navigation sensors and algorithms needed to reliably and safely interact with debris [5]

The harpoon is being studied due to these key features:

- Low mass and size leading to the possibility of many harpoons on a single host spacecraft
- Relative simplicity leading to high reliability, low development risk and low cost
- High firing speed means that it is compatible with objects spinning at fast rates
- Compatible with satellites and rocket bodies
- Easy to test on the ground with highly representative targets

2 TYPICAL TARGET PROPERTIES

The wide variability in the types of objects makes it difficult to define a ‘typical’ target and therefore a key goal of the development is to design a solution which can be used on many different types of object without modification. This significantly reduces cost and risk, whilst also enabling mission level flexibility in target selection, e.g. the target can be selected after launch.

It has been shown [1] that the most useful targets for removal have high mass and collision probabilities ($M{*}P_C$). Below 1100 km altitude these include [5]:

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- SL-3 R/Bs (Vostok second stages; 2.6 m dia. x 3.8 m length; 1440 kg dry mass)
- SL-8 R/Bs (Kosmos 3M second stages; 2.4 m dia. x 6 m length; 1400 kg dry mass)
- SL-16 R/Bs (Zenit second stages, 4 m dia. x 12 m length; 8300 kg dry mass)
- Ariane 4 R/Bs (1700 kg dry mass)
- CZ-series R/Bs (1700–3400 kg dry mass)
- H-2 R/Bs (3000 kg dry mass)
- various Meteor-series and Cosmos spacecraft (masses from 1300 to 2800 kg)
- satellites such as Envisat (8000 kg) and other earth observation satellites

Obviously it is not possible to identify any particular objects which might be de-orbited first, but some initial conclusions can be drawn in terms of target configuration, mass, and potential for harpoon capture:

Satellites:

- Appendages such as the solar array can be targeted. Typical solar arrays are constructed from CFRP skins and aluminium honeycomb cores. However they are not normally designed to take loads and would break apart under typical satellite loads >10N.
- Walls can be targeted. Access panels have nothing mounted on them, whereas other panels may have electronics boxes, pipework and harnesses. Typical walls are constructed from aluminium skins and aluminium honeycomb cores, up to 50mm. They are normally covered with MLI.

Rocket bodies / upper stages:

- The main engine nozzle(s) can be targeted. However this is not considered further because the mechanical state after firing is generally not known and is not a reliable loading point.
- The payload adapter can be targeted. This is typically a metallic or CFRP cone.
- The inter-stages or main tank shell can be targeted (if depressurized to a sufficiently low level to avoid explosion). Typically these are 1.6-3mm solid 7000/2000 series aluminium (possibly with local reinforcements or stringers). The level of pressurization which is 'safe' is not known but in fact could be rather high (i.e. a significant fraction of the operating pressure) because of the leak before burst criterion which is normally applied to design. However it should also be stated that nearly all discarded rocket bodies are either passivated, so old that they should have leaked by now, or depleted with low residual pressure. I.e. the majority of rocket bodies should be possible to target with a harpoon. The exception is recently failed rockets which have not reached the desired orbit and are fully fuelled.

Masses for all objects are up to 9 tons. Considering the dynamic properties, some conclusions can be drawn from past observations using flash measurements and radar observations [6,7]:

- Rocket bodies decay over about 250 days to a few degrees/sec about a primary axis. As a starting point 5°/s could be taken as typical.
- Satellites can exhibit faster spin rates, typically tens of °/s. As a starting point 10°/s could be taken as typical, enveloping most targets. Decay is also seen, although at a slower rate than for rocket bodies.

The results of the target characterization are shown below and have been used to initiate the harpoon design.

Table 1. Target property envelopes

Satellites	Box with appendages Al/Al honeycomb up to 50mm Internal equipment or honeycomb, possibility for blank access panels
Rocket bodies	Cylinder with diameter 2-2.5m dia. or payload adapter Solid 2000/7000 series aluminium plate Internal stringers and reinforcements Potentially some residual pressurization
Spin rate	Up to 10°/sec in a principal axis, possibly slow rotation about others
Mass	<= 9000kg

3 HARPOON SYSTEM DESIGN

The mission concept starts with a chaser spacecraft which rendezvous with the target using an autonomous guidance and navigation system. After a characterization phase the chaser moves to a close distance (nominally 10m) and fires the harpoon into a preselected area of the target's surface. In the baseline concept the harpoon is attached to the chaser with a tether which allows the chaser to apply forces and torques to the target so that it can be de-tumbled (if necessary) and de-orbited (either by the chaser or by a secondary 'deorbit pack'). The de-orbit can either be 'high thrust' (could be as high as 1600N), using a chemical propulsion system or 'low thrust' using electric propulsion or passive methods, e.g. drag augmentation.

The harpoon system consists of the harpoon itself, a firing system, and a tether. The harpoon consists of:

- a barbed tip to prevent pull-out after impact
- a crushable, controlling penetration depth
- a shaft to interface with the firing system

- a stabilizer for ground testing

Detailed simulations and tests have shown that the harpoon is stable during flight in air and in vacuum, but the stabilizer is implemented to provide additional static margin for ground testing as a risk mitigation. The length of the harpoon is 585mm and the mass is 0.3kg.

The currently envisaged firing system is based on compressed nitrogen. Pointing of the harpoon would be done by the host spacecraft. The advantage of the gas firing system is that it is based on well proven technology and can be used for several harpoons mounted on the host. The gas system allows the firing energy to be varied in-flight which helps to tailor the launch to different targets. It also allows the simultaneous firing of multiple harpoons which could be a good option if redundancy is required. During launch the harpoon is prevented from movement by a hold-down and release mechanism (HDRM).

An alternative 'hot gas' firing system has also been designed for the case where only a few harpoons are required and there is no need to vary the firing energy for each target. In this case the compressed gas system is removed and each harpoon includes a small pyrotechnic gas generator, similar to those used for propulsion system latch valves. On application of an electric current hot gas is generated forcing the harpoon out of the barrel and a breakaway pin, which is used to hold the harpoon in the barrel, to fracture.

Finally, a Dyneema® tether is attached between the firing mechanism and the harpoon. The tether is stored in a spool container which opens passively upon firing and minimizes the force on the harpoon. The Dyneema tether is sized for the maximum force to be applied during de-tumbling and de-orbit operation (1.6kN), however forces up to 10kN should also be possible by increasing the tether diameter.

Table 2. Main parameters of the harpoon

Target mass	<= 9000kg
Target dimensions	Unlimited
Target materials	Aluminium/aluminium honeycomb sandwich Solid aluminium plate
System max dimensions	585mm x 40mm
System mass	8kg for 2 harpoon system + 1.3kg for each additional harpoon
System power	20W peak
Typical imparted ΔV to host spacecraft	0.01 m/s
Debris generated	Virtually zero; occasionally a few flecks <0.5mm inside the target
Accuracy	<5cm @ 10m
Firing distance	>= 10m

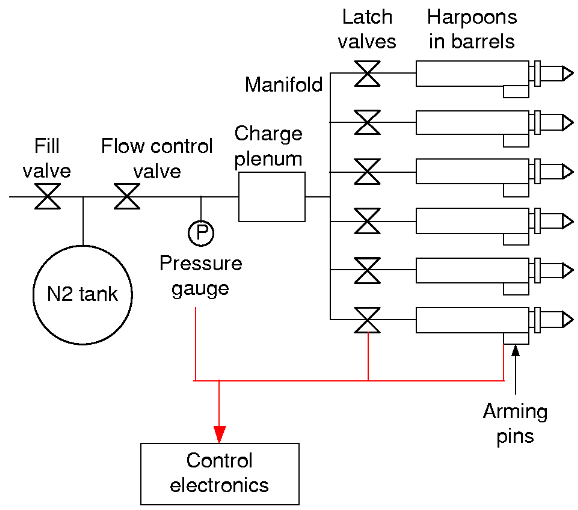


Figure 1. System concept for multiple-launch option

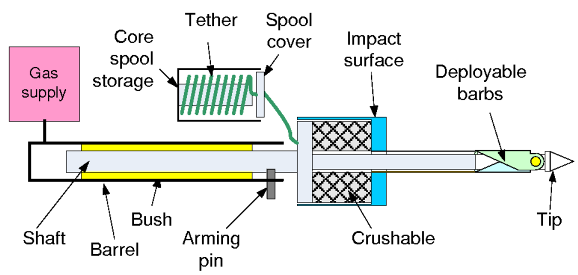


Figure 2. Harpoon schematic concept

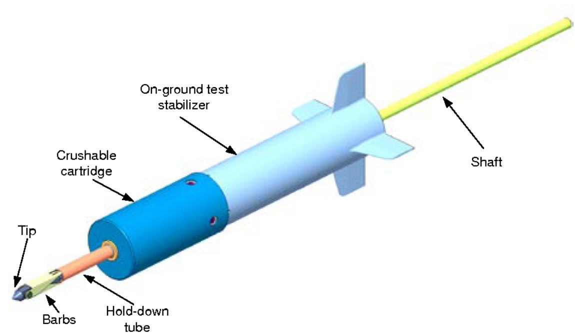


Figure 3. Harpoon CAD model

Figure 4. Manufactured harpoon with stabilizer

4 TEST CAMPAIGN

The purpose of the hardware development is to raise the harpoon TRL to 4 (laboratory testing) as well as to understand the design sensitivity to different modes of operation. Three types of testing have been planned:

Qualitative understanding : these tests have been carried out using a commercial spear gun and semi-representative harpoon against aluminium/aluminium honeycomb sandwich panels. The goal is to understand the behaviour of the impact and the type of damage which is created.

Quantitative characterization : these tests have been carried out with a compressed gas gun and representative harpoon. The goal is to prove the feasibility on representative targets and understand the performance sensitivity to design parameters. Particular aspects which have been investigated are:

- Required penetration force/energy of panels
- Performance of firing system
- Effectiveness on different targets (particularly materials and construction)
- Effect of impact angle
- Generation of debris
- Effect of target satellite internal equipment and heat-pipes on penetration
- Targeting accuracy and range
- Stability over short flight range
- Effect of tether on flight

These tests also support the development and correlation of performance modelling which will be used to improve the design and reduce future risks.

To simplify the testing it has been carried out in air and in a horizontal configuration which implies that the harpoon flight will be affected by both aerodynamic forces and gravity. Therefore additional testing has been carried out to characterize these effects and ensure that the results can be applied to the in-orbit configuration.

Figure 5. 2m horizontal test chamber

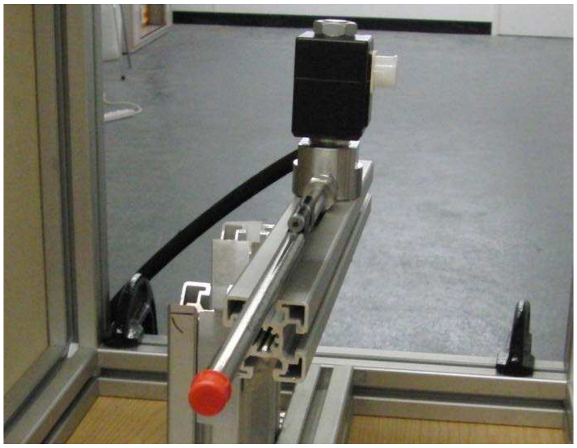


Figure 6. Compressed gas gun

Full scale tests : the above tests have been carried out on a small flight distance of 2m since they centre primarily on launch and impact of the harpoon. The full scale tests have been designed to investigate the flight phase more accurately over a range of 10 m (corresponding to the envisaged firing distance in-orbit), as well as develop future verification methods which would be used on a flight mission (including instrumentation and, importantly, develop and validate safety protocols). Furthermore the tests have been carried out using large targets which are more structurally representative of the types of object which will be encountered in a mission. The first class of target is a large aluminium/aluminium honeycomb sandwich panel suspended in a free-free condition – i.e. the worst case for dissipation of the harpoon energy into panel vibration. The second class of target are aluminium/aluminium honeycomb sandwich panels mounted onto a rotating test stand. These panels are clamped at the edges and are structurally more representative of a real spinning satellite target.

For each test high speed video footage was used as the primary measurement tool, along with measuring the failure behaviour of the targets and any debris generated during the impact.

5 TEST RESULTS

5.1 Qualitative understanding

Initial testing was performed with a fixed firing speed and aluminium/aluminium honeycomb panels. The results showed:

- The harpoon causes only local damage in the aluminium panels, which are not damaged in any other way. Structural failure is by crushing, peeling and shearing rather than plugging.
- The barbs successfully deployed without the need for actuation forces, passively opening

when the harpoon was loaded in tension after impact.

- Only a small amount of debris is generated, consisting of a few flecks (sub-mm size) of aluminium. The debris is internal to the target and therefore would not escape the target satellite or rocket body. Subsequent examination indicated that the main process was crushing of the peeled internal skin causing fragments to break-off inside the target.
- Application of a 1600N static load to the harpoon caused no observable damage to the harpoon or panel. Therefore this shows that the concept is robust to de-orbit and de-tumbling forces.
- The presence of harpoon holes near to penetration points did not affect the ability to withstand pull-out forces which shows that a satellite could be harpooned several times if necessary without affecting the overall capture and de-orbit concept.

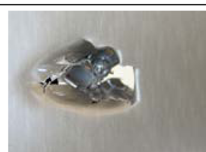
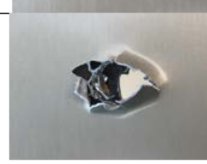
	AOO = 0 degrees	AOO=45degrees
Front Face		
Rear Face		

Figure 7. Front and rear face of test pieces after impact for Test 1) (AOO=0°) and Test 2) (AOO=45°)

Figure 8. Successful barb deployment, note the second impact hole nearby showing the peeling nature of the panel skin failure

5.2 Quantitative characterization

The first set of tests was carried out to characterize the gas gun and characterize the flight behaviour of the harpoon. First a solid rod was fired at varying pressures to check that the system was behaving as expected. Then the harpoon, without a crushable, was fired at varying pressures. The results were then used to correlate a 1D CDF simulation which models the dynamic behaviour of the gas in the system and the harpoon acceleration. The results, shown in Fig. 9, show reasonable agreement, although tend to slightly underestimate the firing velocity at low pressures and overestimate the velocity at high pressures. This is believed to be due to way that the solenoid valve, which actuates the firing, has been modelled and eventually a more complex model could be required. However at this stage the correlation is suitable for further design work.

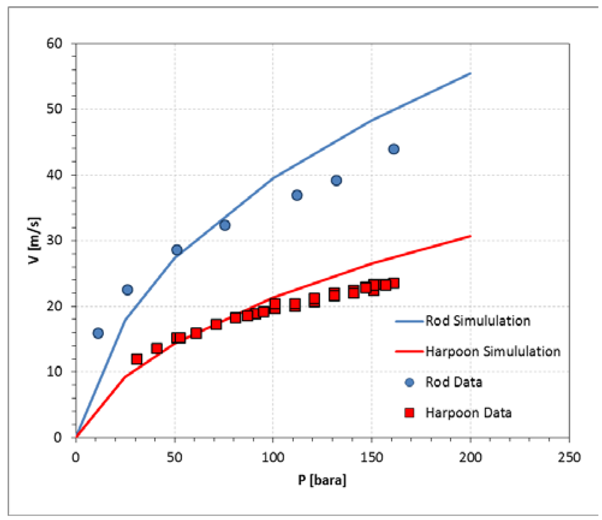


Figure 9. Characterization of the harpoon firing system

A series of tests were then carried out on aluminium/aluminium honeycomb (the most common type of panel material for satellites), CFRP/aluminium honeycomb (occasionally used for high stability payload panels) and solid 2024 series aluminium plate (representing rocket bodies/upper stages) panels to observe the behaviour of the impact. Tests were carried out without a crushable so that the true impact energy could be varied (i.e. without any attenuation). The results showed that a 10 cm thick Al/Al panel could be fully penetrated with 21 bar firing pressure. A similar pressure was recorded for a 25 mm thick CFRP panel.

For the aluminium panels even up to the maximum firing pressure the failure mode was still seen to be peeling on the rear (internal to satellite) skin. In general no debris was recorded, although on a few tests tiny pieces ~0.1mm in size were found on the rear side.

For the CFRP panels a considerable amount of debris was generated on the rear side of the panel. On the front side (space side of the satellite) the honeycomb tends to support the laminate and prevent fracturing. Therefore only small (typically 1-5mm) single layer shards of CFRP are generated. On the rear side, however, the laminate tends to separate away from the honeycomb and fracture along the lay-up of the CFRP, occasionally generating long (10-20mm) single layer shards.

A second set of tests was performed on CFRP panels covered with MLI on the front of the panel, which is actually representative of most real CFRP panels in space. The MLI pack consists of 1 Kapton outer layer and 6 Mylar inner layers with Dacron spacers between them. This is a reasonably typically layup for spacecraft insulation (note, many ESA missions will have 10 layers of Mylar, however this will only improve debris capture, any resistance to the harpoon penetration will be minimal). The edges of the CFRP panel have been taped to represent a large area of MLI covering a panel. The resulting impacts showed an almost total elimination of the debris generated on the front (space facing) face of the panel. A similar amount of debris was still generated on the face which would be internal to the target.

The situation for the solid aluminium plate was complicated due to the lower than expected performance of the solenoid valve which meant that the maximum designed firing speed could not be reached. There was insufficient energy to penetrate the plates in a single shot and therefore multiple shots were used to demonstrate full penetration. This was also very instructive in demonstrating the precision of the harpoon since it r equired to hit a targeted spot with accuracy ~4mm at 2m several times. The results showed that the harpoon can penetrate solid aluminium plates, representative of real rocket bodies, without damage to the harpoon itself. The demonstration also clearly showed the peeling nature of the fracture and the absence of observed debris on either side of the impact.

Figure 10. Penetration of Al/Al honeycomb (note barbs removed to show panel failure mode)

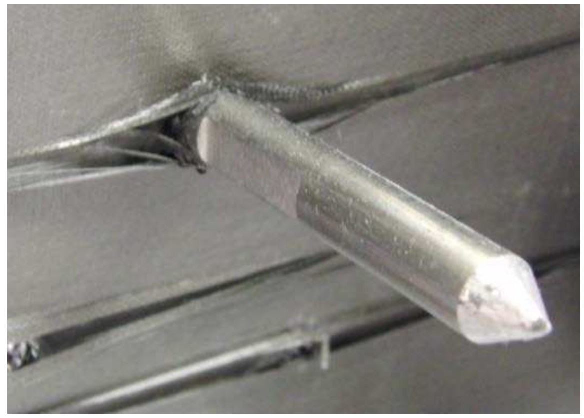


Figure 11. Penetration of CFRP/Al honeycomb

Figure 12. Penetration of 2mm thick Al 2024 plate

Figure 13. Penetration of CFRP/Al honeycomb with MLI on the outer face

5.3 Full scale tests

Two types of full scale test have been carried out over a distance of 10m. The first was a set of firings into a large aluminium/aluminium honeycomb panel (Fig. 14) from the Stevenage production line. The panel was suspended using elastic cord so that it was essentially in a free-free boundary condition. This therefore simulates a target which is very lightweight (<1kg) and in zero-g – i.e. a v ery worse-case target, offering only intrinsic panel stiffness as a resistance to impact. Furthermore the free-free condition means that the maximum energy could be dissipated on impact by vibrational modes in the panel.

The harpoon was fired over 30 times into a single panel, as shown in Fig. 14. Overall the targeting accuracy was a radius of 8cm (1σ), excluding a few shots at different pressures during set-up and also to investigate the effect of pressure on targeting height. This was rather impressive given that no special measures were taken into the design to ensure good accuracy (e.g. high tolerances), and the accuracy of the flight system would be expected to be far better than this demonstration. Interestingly the panel showed excellent structural integrity even after being struck so many times which leads to high confidence that even after a harpoon impact, a debris object will still remain structurally sound and not break apart during subsequent de-tumbling and de-orbit activities. The repeatability of the targeting also gave good confidence in the safety of firing over this distance as well as the ability to place very expensive high speed camera equipment close to the impact without risk.

The impact of the harpoon into a non-rigidly supported panel as found to be identical into rigidly supported panels. This gives confidence that testing can be carried out with rigid samples and the results carried over to a case more representative of zero-g.

In all cases the behaviour of the impacts at 10m was identical to the shorter (2m) distance and no significant loss of speed (due to drag) was found over this distance. This shows that in-vacuum testing is not critical for future iterations of the design. The flight profile was still aerodynamically stable and the only issue with this test was gravity causing the flight to be parabolic. In the future a v ertical test configuration could be used, although this would require a tower >10m.

A second set of tests has been carried out by firing the harpoon into panels mounted on a rotating assembly, shown in Fig. 15. This allows large panels to be tested with internal equipment or more complicated configurations (e.g. we can simulate appendages). Since the assembly is motorized, but with a slip clutch, it is possible to simulate capturing objects spinning up to 6 deg/s and applying a de-spin torque without interference from the motor. Initial testing has been carried out over a distance of 10m, again showing that the harpoon behaves exactly as expected, even at incidence angles up to 45 deg. In addition the tether has been tested and filmed at high speed, indicating that the tether deploys correctly and does not significantly affect the flight path or stability of the harpoon. In the future the size and representativeness of this facility could allow us to simulate the complete capture and de-tumble process, including vision based relative navigation.

Figure 14. Lightweight single panel suspended with elastomer cord and penetrated multiple times at 10m

Figure 15. Rotating satellite simulator

6 NEXT STEPS

A simple, lightweight harpoon system has been designed for capturing objects up to 9,000kg. Testing has given good confidence in many aspects of the harpoon design. The next steps should include:

- Replacing the valve in the firing system to allow the highest design energies to be reached and to complete the testing with solid aluminium plates
- Modelling the flight phase and aerodynamics, with correlation to the test results

- Modelling the impact and penetration behaviour, with correlation to the test results
- Improving various aspects of the design, building on the lessons learnt from the testing, and validating them with the test facility
- Improving the tolerance control in the manufacturing to determine the best accuracy which can be achieved
- Testing the end-to-end capture and de-tumbling process

These actions will allow the complete flight system to be designed with full confidence and the end-to-end capture of a real object simulated with high precision. The final steps will be to produce an engineering qualification model of the flight system, and then build and test it.

6.1 Alternative Concepts

Two additional concepts are currently being pursued.

Although the original concept was designed for removing a large target with controlled re-entry we have also demonstrated effective capture of lightweight debris. Therefore we are investigating the accommodation of a deployable passive drag device onto the harpoon (and no tether).

Eliminating the need for the host/firing spacecraft to de-tumble and de-orbit the debris would lead to a large simplification. The possibility to implement thrusters on the harpoon could be very interesting for some types of object.

7 CONCLUSIONS

A harpoon capture system has been developed for space debris which shows great promise for further development. Using internal funding a great deal has already been learnt about the harpoon and, in particular, many key aspects have already been demonstrated:

- The basic concept has been shown to be capable of penetrating real satellite panels and solid aluminium plates
- Robustness to forces typical of envisaged de-tumbling and de-orbit methods has been demonstrated
- Testing with both small and large objects demonstrates the versatility of the method and ability to successfully penetrate lightweight objects (~kg) with virtually no support (i.e. similar to the zero-g environment)
- The ease of testing has been demonstrated with the possibility to conduct as many as 50 firings in a day
- By multiple capture of a single panel, the robustness of the spacecraft structures to penetration and de-orbit forces has been demonstrated
- The generation of additional debris has been shown to be very low and internal to the target
- The flight dynamics over 10m horizontal flight have been shown to be stable and repeatable
- The accuracy over 10m has already been shown to be 8cm radius without any specific design
- Capture of objects spinning up to 6 deg/s has been demonstrated
- Models have been developed which are being correlated with the testing

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