DEBRIS DE-TUMBLING AND DE-ORBITING BY ELASTIC TETHER AND WAVE-BASED CONTROL

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ABSTRACT

This paper proposes a novel technique to control a completely passive piece of debris, using an actively-controlled, chaser spacecraft, connected to the debris by an elastic tether. An elastic tether has many advantages over robotics, for safe capture, de-tumbling and de-orbiting, but, when slack, there is loss of control and the danger of entanglement and collision. A single chaser control strategy is proposed which combines post-capture de-tumbling with stack GNC for controlled de-orbiting. The control strategy is motivated by elastic wave ideas. The chaser simultaneously imposes a target motion on the debris while absorbing tumbling, rotation and vibration energies coming from it, while also causing the tether to approach its natural length asymptotically, without becoming slack. The control strategy is very robust to debris parameter uncertainties, is simple to implement, and is energy efficient. The method is verified by numerical simulation of de-tumbling, of imposing a delta-v in an arbitrary direction on the stack, and for a complete controlled de-orbit. Aspects are also verified experimentally in a 2-D simulation using two hovercraft.

Index Terms—Debris removal, elastic tether, stack control, de-tumbling, mechanical waves, wave-based control

1. INTRODUCTION

We consider active debris removal, by a "chaser" spacecraft, of a target item which may be completely passive, mechanically complex, flexible, fragile, with uncertain parameters, probably tumbling, and which may have potentially unstable residual propellant and batteries. The chaser is to control the target debris using an elastic tether, which might be attached by a net.

Compared with capture involving a robotic arm, an elastic tether is lighter, mechanically simpler and safer. It lessens unwanted interference between debris and chaser, and reduces jerk on both. But debris control via an elastic tether presents interesting control challenges. The control authority of the chaser depends on the tether's being taught. A taught tether however will lead to acceleration of chaser and debris towards each other, potentially leading in turn to loss of control, and (depending on initial relative velocities) tether entanglement with the spacecraft, stack de-orientation, and/or chaser-debris collision.

In general the chaser's control system, besides controlling its own motion, needs to achieve a number of additional tasks via the tether, as follows:

a) de-tumbling of the debris, regardless of the initial tumbling complexity and orientation of the dominant spin axis;
b) stack stabilization;
c) subsequent imposition of one or more controlled delta-v manoeuvres on the stack, in arbitrary directions with respect to the line of the tether;
d) control of pendular and other swinging behaviour during burn;
e) coasting without entanglement or collision;
f) controlled de-orbit through the upper atmosphere, ideally until final re-entry towards a target area on Earth.

We propose a single control strategy to meet all these demands, which is robust to uncertain parameters, robust to chaser dynamic limitations, simple to implement, safe, requires minimal sensing, makes minimal demands on the chaser design, and is energy efficient.

2. THE MAIN IDEA: MECHANICAL WAVES

To understand the control strategy, first consider a much simpler system, comprising two masses connected by a spring. The left hand mass has an active position control system, the right hand one is passive. (For this initial explanation, the spring is standard, not a tether, and rightwards accelerating motion is considered.) The equivalent challenge in this simple 1-D system is how to control the motion of the actuated mass (directly), so as simultaneously to control (indirectly) the passive mass, combining position control and active vibration damping.

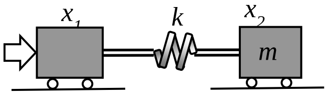

Fig.1. Simple, actuated-mass, spring and passive-mass system

If the system starts from rest, any rightwards motion of the active mass will cause an initial compression of the spring, which both pushes the second mass and pushes back on the active mass. The second mass starts to move, eventually overshooting and tending to extend the spring. We interpret this two-way interaction between the masses as mechanical waves, travelling from the active mass to the dead mass and back again. For the moment consider the wave variable as displacement. (Later velocity waves will also be considered.) On arrival back to the active mass, the waves are either reflected, or absorbed, or more generally, partly reflected, partly absorbed. Continuing motion of the active mass continues to launch motion waves into the system and to respond to returning waves. The two-way propagation of motion waves are easier to imagine if the tether (or spring) has significant distributed mass, or in a string of many masses and springs. But the counter-propagating wave idea can be justified and quantified even for just the two lumped masses and a (massless) spring shown in Fig.1, or for tether which is assumed massless.

We quantify the waves passing through the point where the active mass meets the spring. We consider the motion there as the superposition of two component motions, one travelling rightwards, from the active mass, into the spring and towards the inert mass, the other leftwards, returning from the inert mass through the spring. These are expressed as respectively

$$a(t) = \frac{1}{2}\left[x(t) + \frac{1}{Z}\int f(t)\,dt\right] \qquad (1)$$

$$b(t) = \frac{1}{2}\left[x(t) - \frac{1}{Z}\int f(t)\,dt\right] \qquad (2)$$

where $x(t)$ is the motion of the active mass, $f(t)$ is the spring force at this mass, and Z is a mechanical impedance term. These notional components, whose sum is the motion of the active mass, are considered to be travelling in opposite directions, through the spring attachment point. This feature is independent of the choice of Z, but a suitable nominal value is $\sqrt{km}$, for theoretical and practical reasons discussed elsewhere.

There are other ways of defining the counter-propagating waves, given in the literature [1-5], but for present purposes this simple definition is more than adequate and leads to very good control.

3. CONTROL BASED ON WAVE IDEAS

Now it is desired to give the system a reference motion over time, $r(t)$. As in Fig.2, the control law, $c(t)$, becomes the sum of half the reference plus the measured return wave, or

$$c(t) = \frac{1}{2}r(t) + b(t) \qquad (3)$$

$$= \frac{1}{2}r(t) + \frac{1}{2}\left[x(t) - \frac{1}{Z}\int f(t)\,dt\right] \qquad (4)$$

The control variable $c(t)$ is the input to the actuator position control system, which therefore attempts to make $x(t) = c(t)$. To help visualisation, consider that, if the chaser response were ideal, so that $x(t) = c(t)$, then the control law would reduce to the very simple form

$$x(t) = r(t) - \frac{1}{Z}\int f(t)\,dt \qquad (5)$$

But even when the chaser response is not ideal (with saturation, delays, and so on), the effect is still similar. The motion of the active mass launches a compressive wave of half the reference into the flexible system. Meanwhile it measures the (separate, distinguishable) extensive wave coming back from the system, and moves to absorb this. These two processes happen simultaneously.

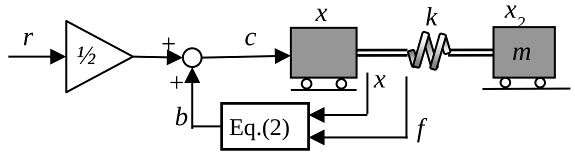

Fig.2 Simple wave-based control system for system in Fig.1

The absorption of the returning wave has two important effects. First is tends to provide active vibration damping, or viscous damping, of the returning wave. This can be seen by differentiating Eq.(4) or (5) wrt time, so that the active mass is seen to be behaving like a viscous damper, with damping coefficient Z, to the pulling on it, by the inert mass, through the interconnecting spring. Second, it moves the system a net amount equal to the other half of the reference input. This is most easily seen for rest-to-rest motion with a real spring. The final momentum equals the initial, so the time integral of the force returns to zero, ensuring the final value of x equals that of r.

If the flexible system becomes more complex, modelled perhaps by a cascade of masses, springs and dampers extending to the right, the same simple control system remains valid. This is so even if the mass and spring values are unknown. In other words, the control system is not model-dependent or even model-order dependent. The measureed returning wave will be different, but so will the motion of the active mass to absorb it. Thus, real-time system identification and adaptive control are happening, with minimal computation.

Besides being robust to system changes, it is also robust to actuator limitations. Imperfect absorption of the returning wave, so that say only 90% is absorbed, means 10% is relaunched into the system, and 90% of that 10% is then absorbed on its return. Thus quickly 100% absorption is approached.

For the present application a few novelties of the basic idea are appropriate.

a) For attitude control about the tether axis, the wave motion is taken as *angular displacement*, with $r(t)$ and $x(t)$ now in radians. Masses become moments of inertia, I, the stiffness is the tether's torsional stiffness, k_t, forces become moments, and the mechanical impedance can be set to $\sqrt{k_t I}$.

b) On the other hand, to achieve a desired delta-v, the wave variable is taken to be *velocity*, with units m/s. So $r(t)$ is now in m/s, and the returning wave becomes $b(t) = \frac{1}{2}\left[\dot{x}(t) - \frac{1}{Z}f(t)\right]$. The skyhook viscous damper action, or energy absorbing, with a velocity proportional to the force, then becomes more obvious.

c) Three, independent, wave-based, controllers control the three components of the velocity. Each works to achieve the appropriate reference velocity while absorbing any tendency for the debris and tether to pull in another direction.

d) For torsional control, when the debris is tending to twist the tether, the equivalent spring can support positive and negative torques. For translational and velocity control however, the tether can support only extensive forces. This has a few consequences, as follows.

e) To cause a deceleration of the debris, the chaser needs to be behind the debris, pulling it backwards. (Obviously, for acceleration, say to a higher, graveyard orbit, the opposite applies.)

f) In all cases there is a free choice of the time profile of the reference input, $r(t)$. For rotations about the tether axis, the only requirement is that it become steady at the target angle, and the reference transient can be arbitrarily short, even instantaneous (i.e. a step input). For velocity control, however, to avoid overshoot of the target velocity by the debris, leading to a slackening of the tether, the reference ramp to target (acceleration) can still be fast (close to a step), but should not exceed a certain maximum rate, determined by system parameters. With this proviso, under wave-based control, the stack velocity then approaches the target asymptotically, leaving the tether unstretched.

4. NET CAPTURE

The method will apply regardless of the way the elastic tether is attached to the debris, including by a shooting net, a harpoon, or by positive net capture. We prefer positive net capture as being simpler, lighter, safer, more complete, and causing less reaction on the chaser. It is illustrated in Fig.3.

This arrangement is simpler mechanically than firing a net, it avoids the need for any kind of gun and associated recoil and required shooting accuracy, it does not need net corner masses, the inflation does not need to last very long, the net size can be scaled for any debris object, and all appendages on the debris (e.g. solar panels) should be positively captured.

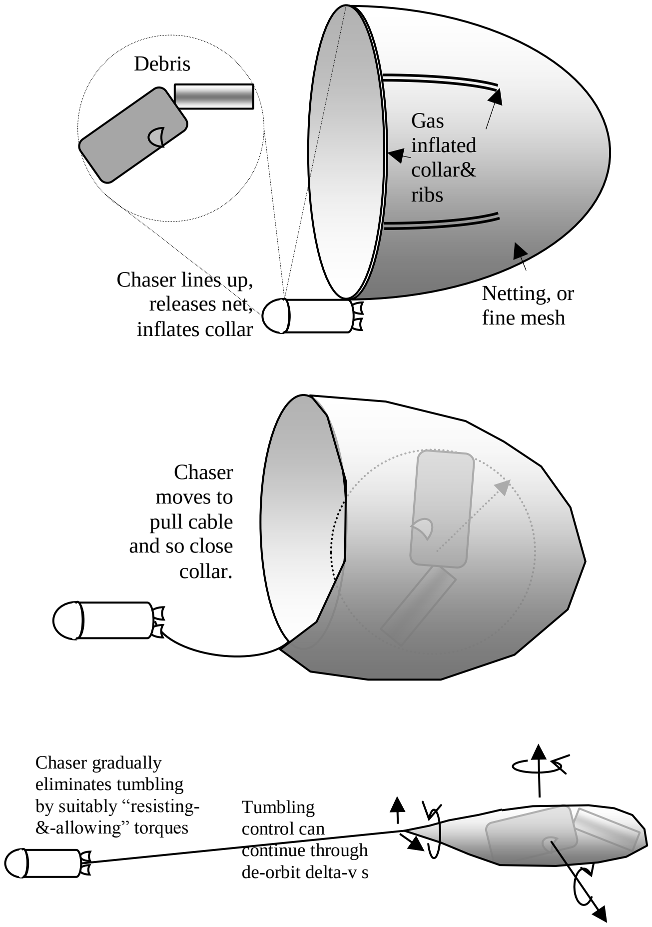

Fig.3 Positive net capture, an alternative to shooting a net.

5. DETUMBLING

Unless the debris is not rotating, or has been de-tumbled before capture, the first challenge for the chaser is to control the tumbling of the debris at the other end of the elastic tether. The nature of this task depends strongly on the orientation of the dominant spin axis (assuming there is one) with respect to the tether line connecting chaser and debris. If these two are aligned, with the tether attachment point close to a *pole* of the rotating debris, then the debris will tend to cause a twisting of the tether, giving rise to a torque on both chaser and debris. On the other hand, if the spin and tether axes are closer to being mutually perpendicular, so that the tether attachment point is closer to the *equator* of the debris, the debris will tend to wrap the tether around itself. This winding-up effect will also cause a pulling of debris and chaser closer to each other. The reality could be a combination of both these effects, perhaps complicated by partial wind-up and slippage. For the first case, the tether torsional elasticity is important, while for the second the longitudinal elasticity is of interest.

For the chaser to bring about de-tumbling of the debris, it will have to supply an angular impulse, about, say, the debris centre of mass, equal and opposite to the initial angular momentum of the debris, also about its mass centre. This applies to any de-tumbling strategy. In the present strategy it does so by working continuously to absorb energy and momentum from the debris, while imposing a reference position.

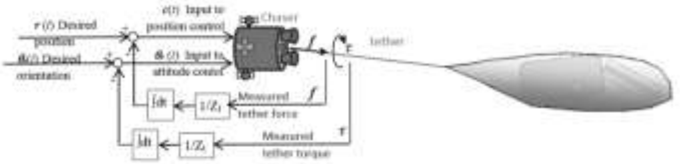

Fig.4 De-tumbling control system

The de-tumbling may also involve a change in the linear momentum of the stack as the chaser responds to pulling by the debris. If so, it will be desirable that this change might also be helpful for the subsequent de-orbit process, that is, that it would tend to reduce the orbital velocity of the stack. This suggests that the chaser should be behind the debris in its orbit, so that all tether pulling would tend to slow it down, thereby making good use of any fuel expended in the process. These and other considerations might determine the tether orientation independently of the debris spin axis.

Post-capture, and before de-tumbling, the debris is therefore potentially pulling and twisting the tether. Wave-based displacement control of the chaser, at the other end, responds to these effects by making it behave like two skyhook viscous dampers, one translational, one rotational. The debris feels an elastic member terminated by a viscous damping member, thereby absorbing or dissipating the tumbling kinetic energy and momentum. The equivalent damping coefficient is the impedance term, Z, set to approximately half critical damping, although the exact value is not critical. Simultaneously with the damping action, the chaser can, if required, also impose a desired motion on the stack, through $r(t)$, to end up in a desired position, velocity or attitude. The chaser both resists the debris motion and yields to it, combining the imposition of desired motion with the right amount of elastic “give”.

6. STACK DELTA-V

Assume the stack is stable, with the tether at its natural length (see below), with debris and chaser at the same speed. It is desired to give the stack a specified change in velocity, delta-v, in a specified direction. To reduce the orbital velocity, the chaser should initially be somewhere behind the debris: to increase the velocity it should be in front. But the tether might not be closely aligned with the desired velocity direction. Any non-alignment will lead to pendular swinging of the debris around the chaser path as it accelerates. The pendular frequency will be of the order of $\sqrt{acc/length}$. Also if the tether line does not go through the mass centre of the debris, the moment of the tether force about the mass centre will lead to rotational oscillations, or yo-yo modes.

The same wave-based control strategy used for de-tumbling also works very well to control all such motions, that is to achieve the target delta-v, to control the debris swinging and other oscillations arising from the manoeuvre, and to finish with the tether again at its natural length. For each of the six degrees of freedom of the stack, a wave-based control system is implemented. For attitude control, it is as before, with each rotational wave-based control system causing the chaser to dampen undesired twisting motion coming from the debris while simultaneously imposing a target attitude. For translation control in 3-D, three wave-based controllers now control the three components of the velocity, working to simultaneously impose the target velocity profile while absorbing components of the tether tension which are tending to pull the chaser in another direction.

7. COASTING AND RE-ENTRY

A single-burn, single delta-v operation could achieve de-orbit, perhaps with little re-entry control. But it might be desired to have the stack coast for longer times, perhaps between successive delta-v operations for orbit transfer manoeuvres or to wait so as to re-enter towards a target zone. During coasting, the tether ideally should not become slack. Yet keeping it at its natural length despite disturbances could require chaser fuel, and having it even slightly taught will cause relative accelerations. One solution is to initiate a slow spin of the stack around its mass centre, thereby maintaining the stack formation for long periods without requiring active control or fuel expenditure.

As the stack enters the upper atmosphere, and if the ballistic coefficient of the chaser is higher than that of the debris, the chaser then needs to go ahead of the debris, to maintain the stack stability and to allow any desired stack control by the chaser. In this orientation, the chaser could, if required, apply control right up to burn-up and break-up. In addition to drag forces tangential to the path, aerodynamic “lift” force normal to the path, and torques associated with centre-of-pressure locations, could also be important. Again, if required, and still active, the controller will work to absorb these and to maintain a reference course.

8. NUMERICAL VERIFICATION

To test the ideas above, full 3-D mathematical models of realistic chaser-tether-debris systems were developed and verified.

First de-tumbling was tested for a range of post-capture scenarios, including different orientations of the dominant debris spin axis to the initial tether direction. The only sensing allowed to the chaser was a measure of the magnitude and direction of the tether force and torque it was experiencing. The chaser control system imposed its own

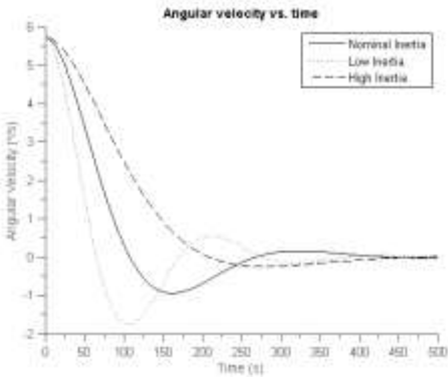

Fig.5 Sample de-tumbling of angular velocity: tuned for half critical damping of nominal debris, but also for double and half nominal moments of inertia with unchanged controller.

attitude and motion control while simultaneously acting as viscous dampers, at about half critical damping, to motion coming back from the debris, as both pulling on, and twisting of, the tether. Two simultaneous but independent wbc systems dealt with absorbing the pulling and the twisting, while simultaneously imposing a desired chaser location and attitude. In this part of the work, the target chaser location was at the tether's length from the debris.

Sample results are shown in Fig.5, for one case. The nominal case has the Z value set for the actual moment of inertia, and the half critically damped response can be seen. Then to test robustness, the moment of inertia was doubled and halved, without changing the controller, and the response remains very good, with comparable settling times. To test robustness further other parameters, which may not be known in practice, were varied by large amounts (nominal multiplied by 0.1 to 10). The control system remained completely stable and steadily reduced the tumbling to zero in each case. To simulate partial tether wind-up followed by slippage, after some winding the tether's free length and winding location were suddenly changed. It was found that the good de-tumbling continued without difficulty.

Then achieving a desired delta-v was simulated, first in 1-D, then 2-D and finally in a full 3-D model with realistic chaser and debris parameters. The mass, dimensions, and inertia matrix of the debris corresponded to those of Envisat. Those of the chaser were taken from the ESA document [15]. The chaser has thrusters up to a maximum 2400 N in any direction, with additional on-board thrusters to provide independent torque to change or maintain attitude. The tether length was 400 m, longitudinal stiffness 100 N/m, damping 0.01 Ns/m. The tether was modelled using 5 springs and dampers and 4 masses

A typical set of responses is shown in Fig.6. The target delta-v is 270 m/s, and the reference change in attitude was set as 45 degrees around each axis, roll, pitch and yaw. It is seen that the control system achieves all the requirements. It maintains the tether always at or above its natural length of 400 m, and at the end of the manoeuvre it returns to this natural length asymptotically, with no undershoot. Thus the tension is always positive. The velocities of the chaser and target track each other closely. The last diagram shows the roll, pitch and yaw profiles for the chaser, the target and the pitch and yaw for the tether. They all approach the target 45 degrees and settle well.

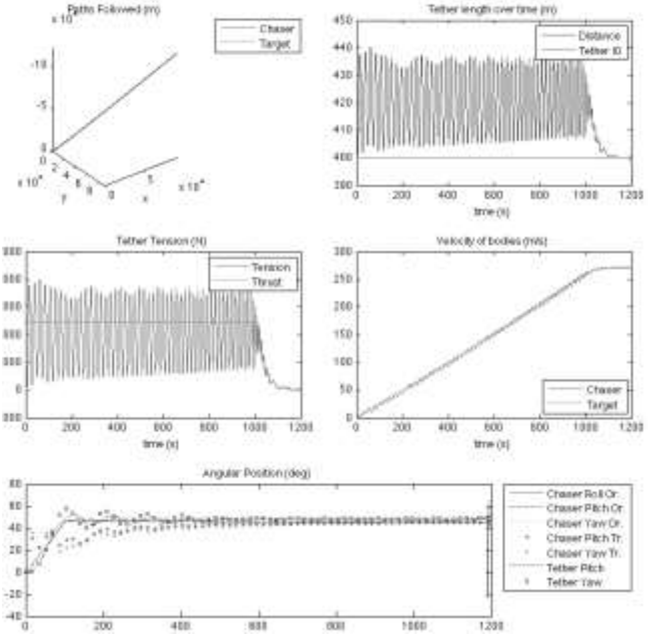

Fig. 6: Control system tested with reference delta-v of 270 m/s and with reference roll, pitch and yaw of 45 degrees.

9. EXPERIMENTAL VERIFICATION IN 2-D

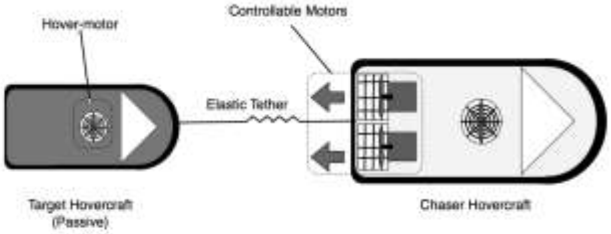

Fig.7 Experimental arrangement for 2-D delta-v manoeuvre

To verify supplying a delta-v to a dead spacecraft in microgravity, two model hovercraft were used, interconnected by an elastic cord. One of these, modelling the debris, was uncontrolled. It simply hovered. The other, modelling the chaser, had an on-board micro-controller, which also interacted remotely with a computer.

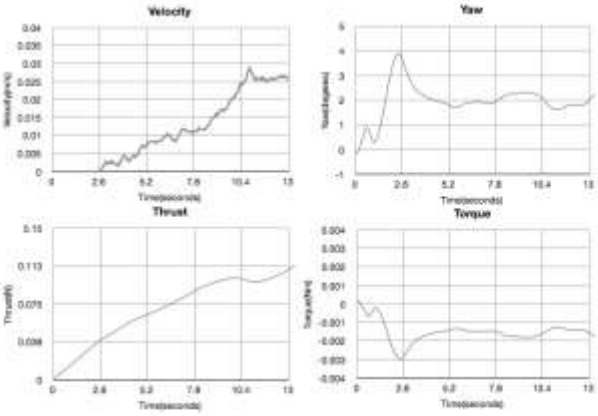

Fig. 8: Velocity and orientation control system results for the chaser hovercraft

Motion control of the chaser model was by two fans giving forward thrust, and a turning moment when driven at different rates.

Sample results are in Fig. 8. A steady acceleration is seen for about 10 seconds where the velocity is just over 0.025 m/s. At this stage, the thrust does not go back to zero as the numerical models might have suggested, but reaches a finite steady-state value. This is due small friction forces that remain, despite the fact that the hovercraft is floating. The yaw angle also settles after about 5 seconds, along with the applied torque. There is a steady state error which is likely due to the coupling between the thrust control and the torque control, as they use the same two driving motors. But the system is operating stably and effectively, and such errors can be addressed.

The robustness of the control system was also tested, in a simple way, by varying system parameters significantly. The resulting variation in the control results was found to be very small. Also robustness to on-board fluid sloshing was simply illustrated by adding liquid container to the towed hovercraft, with little observable deterioration in the controlled response.

10. DE-ORBIT SIMULATION

Simulation of controlled de-orbits of an Envisat-like debris object under wave-based control were carried out. A simple drag model was used to calculate the drag force on both the chaser and debris. A full aerodynamics analysis was outside the scope of this project, but could be added without special difficulty. It was also assumed that the drag caused no moments on either debris or chaser. The atmospheric density was calculated using the NRLMSISE-00 model from the US Naval Research Laboratory. The cross sectional area used was 2.5 m^2 for the chaser and 16 m^2 for the target. Mehta et al. [16] have studied drag profiles on satellites such as the GRACE satellite and the Hubble Space Telescope. While they study such effects as the angle of attack, they give a drag coefficient of 3.8 for the Grace satellite. This value was adopted here for both the chaser and debris. Again, more refined and precise drag estimates could be incorporated in future work.

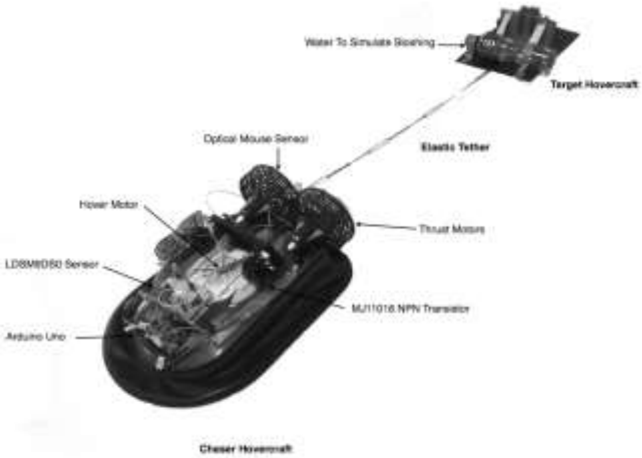

Fig.9 Active hovercraft controlling passive hovercraft with on-board sloshing fluid via elastic cord

Both single-burn and double-burn de-orbits were investigated. The single-burn manoeuvre required 962 kg of propellant. For the double-burn test the first step was to lower the orbital radius to 6880 km (500 km altitude), a new target was set to lower the radius to 6420 km (50 km altitude). This new elliptical orbit took the system to the final target location and perigee. To land in the target, SPOUA, location, the position for initiating the entire process was determined by iteration. The cylindrical map in Fig.9 shows the resulting successful two-burn de-orbit manoeuvre.

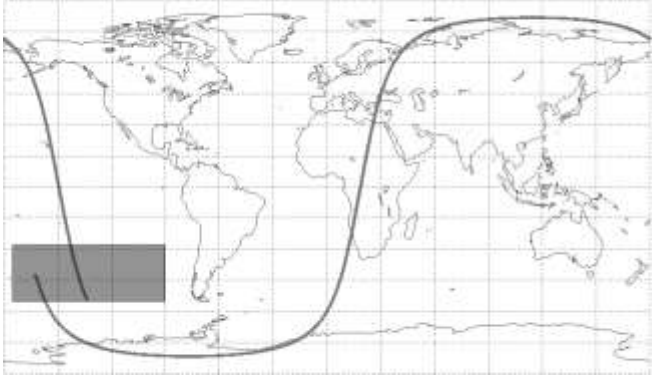

Fig 9: De-orbiting path from the model landing successfully in the SPOUA (moving from right to left)

11. CONCLUSIONS

In the wave view of a flexible system, with an actuator at one end and a passive load at the other, motion passes a given point in two directions simultaneously. Rest-to-rest control consists of inserting energy/momentum into the system from the actuator and then absorbing it, in just the right way to dampen vibrations yet leave behind the desired motion. This simple idea leads to control which is easy to implement and very robust to unknown or un-modelled effects in the system, even such quasi-chaotic effects as liquid sloshing.

The paper has shown that this wave-based control can be used to get an active chaser spacecraft to de-tumble a passive spacecraft of uncertain dynamics. Then the same basic idea can be used to impose a controlled change in velocity on the chaser-tether-debris system in an arbitrary direction, while keeping the tether at or above its natural length, thereby avoiding tangling or collisions. Again the same idea can achieve a controlled de-orbit to a target location, if required maintaining control until final burn-out.

The numerical and experimental simulations verified the practicality of the ideas.

12. REFERENCES

[1] O'Connor, W.J., "Wave-like modelling of cascaded, lumped, exible systems with an arbitrarily moving boundary" *Journal of Sound and Vibration*, 330(13):3070-3083, June 2011.

[2] O'Connor, W.J., Habibi, H., "Wave-based control of under-actuated flexible structures with strong external disturbing forces" *Institute of Engineering and Computational Mechanics*, May 2012.

[3] O'Connor, W.J., "Wave-Based Analysis and Control of Lump-Modeled Flexible Robots" *IEEE Transactions on Robotics*, 23(2):342-352, April 2007.

[4] O'Connor, W.J., Ramos de la Flor, F, McKeown, D. J., Feliu. V., "Wave-based control of non-linear flexible mechanical systems" *Nonlinear Dynamics*, 57(1-2):113-123, July 2009.

[5] Ming Zhu. "Wave based modeling and control of flexible mechanical structures", PhD thesis, University College Dublin, 2014.

[6] Misra, A.K., "Dynamics and control of tethered satellite systems" *Acta Astronautica* 63 (2008) 1169 – 1177

[7] Suna, G., Zhub, Z.H., "Fractional order tension control for stable and fast tethered satellite retrieval" *Acta Astronautica*, Volume 104, Issue 1, November 2014, Pages 304–312

[8] Nishida, Sh, Kawamoto, S., "Strategy for capturing of a tumbling space debris" *Acta Astronautica*, 68(12):113-120, January 2011.

[9] Chatterjee, A., Fitz-Coy, N., "Spacecraft detumbling through energy dissipation" NASA. Goddard Space Flight Center, *Flight Mechanics, Estimation Theory Symposium*, 1992; p 23-37

[10] Wormnes, K., R. Le Letty, L., Summerer, R., Schonenborg, O., Dubois-Matra, E. Luraschi, A. Cropp, H. Krag, Delaval, J., "ESA technologies for space debris remediation" In *6th IAASS Conference*, volume 1, Montreal: European Space Agency, 2013.

[11] V. Aslanov and V. Yudintsev. Dynamics of large space debris removal using a tethered space tug. *Acta Astronautica*, 91:149–156, 2013.

[12] V. Aslanov and V. Yudintsev, "Behavior of tethered debris with flexible appendages", *Acta Astronautica*, 104:91–98, 2014.

[13] H. Schaub T. Valery L. Jasper, C. Seubert and Evgeny Yutkin, "Tethered tug for large low earth debris removal", *American Astroautical Society*, Charleston, South Carolina, 2012.

[14] H. Schaub L. Jasper. Input shaped large thrust maneuver with a tethered debris object. *Acta Astronautica*, 96:128–137, 2014.

[15] Cdf study report e.deorbit. Technical report, European Space Agency, 2014.

[16] E. Lawrence, R. Linares, D. Higdon, P. M. Mehta, A. Walker and J. Koller. "Modeling satellite drag coefficients with response surfaces". *Advances in Space Research*, 54:1590–1607, 2014.