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Paper Title: Ballute Aerocapture Trajectories at Titan

Short Abstract ---

Ballute Aerocapture Trajectories at Titan

Aerocapture at planets and moons with atmospheres using a towed, inflatable ballute system has the potential to provide significant performance benefits compared to traditional all propulsive and aerocapture technologies. This paper discusses the characteristics of entry trajectories for ballute aerocapture at Titan. These trajectories are the first steps in a larger systems analysis effort that is underway to characterize and optimize the performance of a ballute aerocapture system for future missions to Titan.

Extended Abstract: --

Ballute Aerocapture Trajectories at Titan

A "Ballute" is a cross between a "balloon" and a "Parachute". The inflated components provide the stiffness needed to maintain the proper shape of a very light weight structure, while the large drag area acts like a parachute to slow the spacecraft rapidly once it enters the upper atmosphere of the target body. Angus McRonald has pioneered the studies of ballutes for aerocapture at several planetary bodies. An interdisciplinary team of engineers lead by Kevin Miller (Ball Aerospace) is starting to take a closer look at characterizing and refining theuse of ballutes for future aerocapture missions. The team includes experts from Ball Aerospace (system engineering), ILC Dover (inflatable structures), NASA Langley Research Center (aerothermodynamics and hypersonic performance verification), and the Jet Propulsion Laboratory (trajectories, mission design, and instrumentation). Preliminary calculations have shown that ballutes might be constructed using existing materials. These large, lightweight inflatable structures provide a significant mass savings over traditional all-propulsive vehicles or aerocapture using a heat shield, especially when a special transfer stage is required to provide power and attitude control during cruise. In addition to the low additional mass of the ballute for aerocapture, one of the fundamental benefits of carrying a ballute is that the primary spacecraft bus does not have to remain tightly packed for cruise, but can be deployed and flown like an orbiter.

All propulsive capture requires that the spacecraft must carry all of the propellant needed for the mission. For low altitude orbiters, the mass of the propellant for a traditional all propulsive spacecraft becomes so large that the useful science payload becomes too small to be cost effective. In some cases, such as missions to Titan and Neptune, it may not be possible to conduct an orbital mission without aerocapture and/or other advanced propulsion technologies. One alternative for reducing the amount of propellant that must be carried is to use atmospheric drag to provide the velocity change required to capture into orbit. The traditional approach is to pack the spacecraft tightly inside a protective heat shield and dive deep into the atmosphere, where the heat shield must provide protection against the extremely large heating rates that will be encountered. Everyone associated with the space program is so familiar with the high heating rates associated with this traditional atmospheric entry, that it would be easy to make the mistake of assuming that high heating is also required for aerocapture. High heating is not required for aerocapture.

Imagine instead the approach used for aerobraking, where the spacecraft is so high in the atmosphere that the heating rate is tolerable even for an unprotected spacecraft. As the area of such a spacecraft is increased, the number of required aerobraking drag passes is reduced. The ballute concept takes this idea to the limit by dramatically increasing the area of the spacecraft so that enough drag is produced to remove the required energy in a single pass through the atmosphere. Since the heating rate is a function of the atmospheric density, while the drag force is a function of both the density and the projected frontal area, the ballute system can be designed so that an unprotected spacecraft could survive the aerocapture heating rates (which would determine the density) if the drag producing area is large enough. Smaller ballutes require higher heating rates, because they have to fly deeper in the atmosphere, but they also weigh less because they require less material, Since using minimal thermal protection for the spacecraft means that smaller, lighter ballutes are required, most of the ballute concepts that our team studied have been for heating rates that can be accommodated by the thin kapton film of the ballute, rather than the heating rates that can be accommodated by most unprotected spacecraft. Since kapton can survive higher temperatures than most spacecraft components, using the kapton thermal limits as the system limit means that the main spacecraft bus must be protected by a lightweight thermal blanket on the side facing into the "wind". The ultimate trade between the weight of the blanket and the weight (and size) of the ballute is made at the system level to assure that the maximum spacecraft payload will be safely captured into orbit.

The trajectory component of our team effort will be described in this paper. A typical ballute aerocapture trajectory begins as a hyperbolic approach trajectory which would fly past the planet if there were no atmosphere. The ballute is deployed and inflated hours or even days before entry, and the aerodynamically stable axis of the spacecraft/ballute system is aligned with the velocity near entry. Upon entering the atmosphere, the spacecraft experiences a large deceleration that reaches a maximum value at a relatively high altitude, and then decreases as the velocity slows down. When the desired separation velocity is reached, it is critically important for the spacecraft to release the ballute to minimize further velocity loss due to drag. Although the deceleration at the time of release is usually large, making the timing requirements of the release small, separation mechanisms have been flown with timing uncertainties of about 10 milliseconds, so the tight timing requirement for the release mechanism is not a showstopper.

In the perfect universe of my computer simulations, the heating during ballute aerocapture for a particular vehicle design is minimized if the periapsis altitude of the approach hyperbola is so high in the atmosphere that the target apoapsis is not achieved (i.e. the ballute is not released) until the spacecraft is almost leaving the atmosphere. Such a trajectory would "barely" achieve the target orbit. In the real world, a very small navigation error, or an atmosphere that was slightly less dense than the perfect universe would mean that there would not be enough drag to achieve the desired orbit apoapsis. A slightly larger error could mean that the spacecraft might not even be captured into orbit, but would leave on a slower hyperbolic orbit than the one it arrived on. A ballute system can accommodate uncertainties in navigation, drag-coefficient, and average atmospheric density by aiming the approach hyperbola lower in the atmosphere than required to barely capture and then releasing the ballute earlier in the drag pass, when enough delta-V had been achieved. There are two limits to the periapsis radius of the approach hyperbolic trajectories that can achieve the desired target apoapsis. The upper limit required releasing the ballute when the spacecraft left the atmosphere, as described earlier. The lower limit requires releasing the ballute as soon as the spacecraft enters the atmosphere, because if the drag from the spacecraft alone is too large, approaching on a lower altitude hyperbola will only result in more drag. Although such lower altitude limit trajectories can be found in the perfect universe, they donÕt use the ballute to produce drag, and are equivalent to a ballistic capture by the spacecraft alone, which would require the heavy heat shield that the ballute system is trying to avoid. A trajectory that approached on this lower limit would have no ability to target the desired apoapsis by choosing the time of release. In between these two high and low altitude extremes is a relatively wide corridor of possible trajectories that can be used to accommodate relatively large uncertainties in approach navigation and atmospheric density.

As the aim point targeted deeper into the atmosphere, the ballute is released earlier. An earlier ballute release means that there is more time for drag to change the velocity of the spacecraft after release. Atmospheric uncertainty before the ballute release can be accommodated by monitoring the actual deceleration of the vehicle, and then modifying the release time. Once the ballute is released, the only way to accommodate atmospheric uncertainty is to use propulsion, which requires propellant. The amount of drag experienced after separation can be reduced by using a larger, but more massive ballute to reduce the density and the drag experienced after separation. The absolute magnitude of the density after separation is less for a larger ballute, because the nominal trajectory can be targeted higher in the atmosphere. Thus there is an implicit tradeoff between the mass of the ballute and the mass of propellant required to clean-up the final orbit. A balanced system design will require targeting the ballute system low enough to provide adequate margins for achieving the desired apoapsis target as the spacecraft leaves the atmosphere, but high enough to minimize the propellant that must be carried to clean up the targeting errors. Since at least one propulsive maneuver is required to raise periapsis out of the atmosphere, the question that must be answered is how much additional propellant is required to accommodate the probable dispersion in the ballute trajectory at atmospheric exit ?

This paper will discuss the current status of the trajectory related issues that factor into the overall ballute system design for aerocapture at Titan. This preliminary analysis was based on simplifying assumptions, such as constant drag coefficients and a nominal (smooth) atmosphere from TitanGRAM. The preliminary trajectories provide data for other team members to begin to size the ballute, evaluate the aerothermodynamic environment, develop separation algorithm concepts, and design an optimum system. Future work will include the effects of more realistic atmospheric effects on the candidate separation algorithms and will include the more realistic drag models from the preliminary aerothermodynamic analyses. Since this study is scheduled to span 3 years, we are only beginning to understand the issues associated with a ballute system. Updated results will be reported in future papers.