THE CASSINI / HUYGENS SPACE MISSION TO EXPLORE THE SATURNIAN SYSTEM

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Abstract: The Cassini/Huygens spacecraft arrived in July 2004 at the planet Saturn and landed on 14. January 2005 the atmospheric descent probe Huygens successfully on the surface of Titan, Saturn's largest moon. This paper reviews the related technical challenges and the solutions with emphasis on control engineering aspects. Addressed is the design of a trajectory to bring a spacecraft of almost 6 t by gravity assisted fly-bys to Saturn, despite this is beyond the direct capacity of available launchers. Remote failure diagnosis is highlighted at the example of the telecommunication link problem detected at the distance of Jupiter. In the course of the 10 years long development process different approaches to the descent control system had been discussed for the Huygens probe to enable a safe landing on Titan, satisfying given schedule constraints. These approaches will be compared and discussed in relation to the finally realized solution.

Keywords: interplanetary spacecraft, mission analysis, tele-diagnosis, tele-operations, planetary entry, descent control.

1. INTRODUCTION

In our solar system the planet Saturn, its rings, and its moons offer a broad range of attractive unsolved questions for scientists. Spacecrafts like Pioneer 11, Voyager 1 and 2 revealed in close fly-bys interesting data, but raised even more new problems. In particular Titan, Saturn's largest moon, proved to be covered by a dense atmosphere. When the Voyager 2 spacecraft approached Titan as close as 5000 km in November 1980, the atmosphere proved to be much denser than expected, such that the spacecraft's instruments could not penetrate it. The main constituent is nitrogen but also a significant amount of methane was found. Thus analogies to the early atmosphere to the prebiotic Earth had been pointed out. Therefore scientists placed a more detailed investigation of Titan as a very high priority objective for planetary exploration. This led to the realisation of the Cassini/Huygens mission in a collaborative effort of NASA and ESA.

Image courtesy of NASA

Fig. 1: Integration of the Cassini / Huygens spacecraft.

While NASA developed the interplanetary spacecraft Cassini (named to honour the astronomer Gian Domenico Cassini (1625-1712), the discoverer of the big gap in Saturn's ring and of four Saturnian moons), the European Space Agency ESA designed the descent probe Huygens (named in memory of the astronomer Christiaan Huygens (1629-1695), the discoverer of Titan).

2. THE INTERPLANETARY TRAJECTORY

Most powerful rockets today can transfer spacecraft of about 1 t into a direct transfer to Saturn, while the launch mass of the Cassini/Huygens was about 6 t. Thus elaborate trajectories had to be planned to realize this mission, taking advantage of appropriately positioned planets for flyby-manoeuvres. This chapter summarizes application of the flyby-technique for the interplanetary transfer as well as for the tour within the Saturnian system (Peralta/Flanagan, 1995, Wolf/ Smith, 1995).

2.1 The Flyby-Technique

When a spacecraft approaches a planet, according to the impulse conservation law, the interaction with planets gravity field might change the direction of the velocity vector, but the incoming velocity equals the outgoing velocity wit respect to the planet (cf. Fig.2).

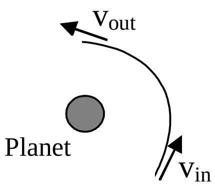

Fig. 2: In the reference system of the planet, the spacecraft's incoming velocity vector has the same magnitude as the outgoing velocity vector, but it might change its direction.

For interplanetary trajectories nevertheless most relevant is the Sun's gravity field. As the planets move with significant own velocity around the Sun, in a solar centric system the velocity vector of the Planet v_{Planet} and of the spacecraft relative to the planet v_{in} are to be added, in order to derive the velocity vector of the spacecraft with respect to the Sun $v_{Sun\ in}$ (cf. Fig.3), before entering the Planet's sphere of influence. The same vector addition is to be applied to derive the outgoing velocity vector after the flyby $v_{Sun\ out}$. So if the fly-by geometry is appropriately selected v_{Planet} can cause a significant increase (as sketched in Fig. 3) or decrease of the spacecraft's velocity with respect to the Sun.

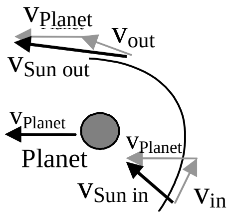

Fig. 3: Analyzing the velocities with respect to a solar centric reference system, taking into account the Planet's velocity.

The design of trajectories including fly-bys depends crucially on dynamic properties of the planets and is thus very sensitive on timing. But also constraints such as minimum admissible altitudes above the planet to avoid interaction with the atmosphere are to be included. This results in mathematically interesting nonlinear problems, where solutions are very sensitive to applied initial values. Thus a trajectory is calculated via several refinement steps from an approximation by patched conics (cf. Battin, 1999).

2.2 The Cassini/Huygens Interplanetary Trajectory to Saturn

The design mass of the Cassini/Huygens spacecraft was in all phases between 5 and 6 t (approximately 3 t were allocated for bipropellant), thus it was obvious that fly-bys need to be included. While during Phase A (1987/1988) a lunch in April 1996 was baseline, here gravity assisted fly-bys at Earth and Jupiter were used to arrive in October 2002 at Saturn. During Phase B (1991/1992) the launch date was postponed to October 1997. Due to the altered planetary positions, the type of trajectory had to be changed. The approach, to fly first towards the Sun to reach Saturn is at the first glance surprising. Thus one of the more frequent fly-by opportunities at Venus has been used in June 1998. A subsequent, combined Venus / Earth flyby in summer 1999 provided a path to a fly-by at Jupiter at end of 2000, leading to a Saturn system arrival in July 2004 (cf. Peralta / Flanagan, 1995).

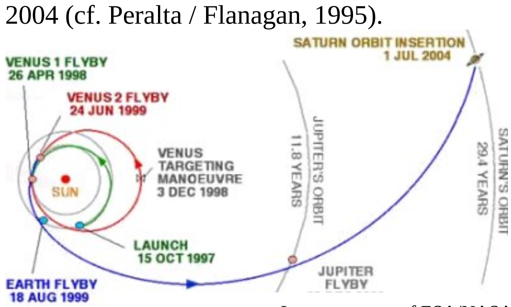

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Fig. 4: The Cassini / Huygens interplanetary trajectory

The launch window for the interplanetary trajectory extended from 4. October 1997 for about one month. On 15 October 1997 the Titan IV-B/Centaur launch vehicle lifted off. There were back-up opportunities in December 1997 and in March 1999, but missing the Jupiter fly by and thus requiring two additional years to reach Saturn.

2.3 The Orbits in the Saturnian System

Similar fly-by techniques are used in the Saturnian system to efficiently modify the flight path for favorable observations of Saturn and its moons. Titan as largest moon is therefore the most suitable object for fly bys. Thus during the 4 year long tour 75 orbits around Saturn and 44 close encounters of Titan will occur, offering also good opportunities for longer term observations (Wolf / Smith, 1995).

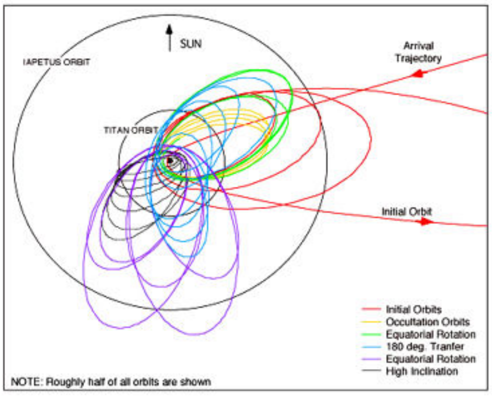

Image courtesy of ESA/NASA

Fig. 5: The 4-year Cassini / Huygens tour in the Saturnian system

3. TELEDIAGNOSIS OF RADIO LINK ANOMALY

At Huygens landing on Titan, the Cassini Orbiter receives the Probe data and stores them for later relay to the ground station. In February 2000 in-orbit performance tests of the receiver on-board Cassini were performed to cover parameter ranges not accessible in ground tests. They revealed that the relay link receiver is not fully compatible with the given data rate and the time-varying baseline link geometry.

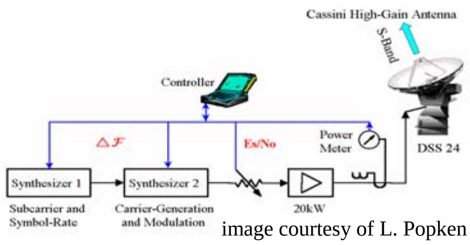

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Fig. 6: The simulation setup to test the Cassini relay link receiver.

At a spacecraft distance as far as Jupiter therefore remote failure diagnosis had to be performed. First the complex test setup, to simulate the Huygens – Cassini signal transfer by a radio emitter on Earth, was supposed to cause the problem. Finally the limited bandwidth of a symbol synchronizer in the receiver was identified as cause of the problem, being too small to accommodate the Doppler shift at the given data stream frequency (Popken, 2004). Despite being a space-proven component, the specific parameter combinations of this mission with respect to frequency offset, signal to noise ratio and data transition density caused cycle slips and related data corruptions. Modeling of the receiver design flaw was therefore a key to redesign a suitable radio relay link geometry. This model had been confirmed in further in-orbit tests.

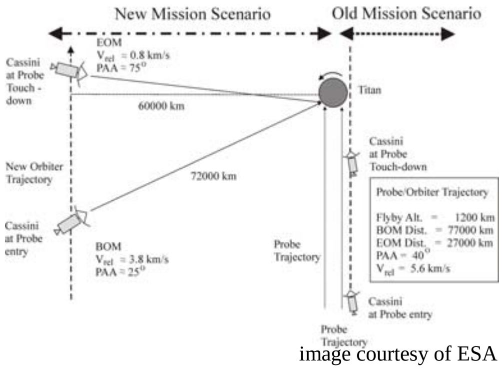

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Fig. 7: The simulation setup to test the Cassini relay antenna.

According to the initial plan, Cassini followed Huygens with only a slight side shift for a close fly by at Titan. When Huygens is decelerated by the Titan atmosphere, then a relative velocity of up to 5.7 km/s occurs between the two spacecrafts. In the revised mission profile to reduce the Doppler effect, a Cassini fly by altitude of 60000 km was selected to stay within an admissible parameter range of the bit synchronizer. In order to realize this new link geometry, the Probe descent to Titan has been delayed to the 3rd Titan encounter on 14. January 2005.

4. THE ATMOSPHERIC DESCENT TO THE SURFACE OF TITAN

At a signal propagation delay of 67 minutes for the distance from Earth to Titan, it is impossible to teleoperate the descent of the Huygens Probe. Therefore only a data link from the Probe to the Orbiter was implemented and no command link to the Probe. Thus after separation of Huygens from Cassini, the Probe had to autonomously control its activities (cf. Schilling / Flury, 1990). At the different implementation phases, related control approaches had been analyzed in order to satisfy all constraints of the descent despite the uncertainties of the atmospheric properties, such as atmospheric density profile, atmospheric dynamics and surface topography.

The scientific instruments required a minimum period for measurements in the different atmospheric layers. For efficient use of the scarce energy resources, activation and coordination of instrument activities should be related according to environment parameters. While the Huygens Probe descends to the surface of Titan, the Cassini spacecraft acts as relay for the transfer of Huygens instrument data towards Earth. As soon as Cassini flys over the visibility horizon of Huygens, the data transfer is finished. Therefore the descent has to proceed fast enough, such that the Probe's surface impact and at least about 15 minutes data transmission from Titan's surface are still covered.
The Probe's descent control system can influence the timing of the following actions

- parachute deployment (a pilote chute deploying a disk-gap parachute with a diameter of 8 m),
- separation from decelerator heat shield (reducing the Probe's mass by 70 kg),
- change towards the smaller parachute (replacing the larger parachute of 8 m diameter by a parachute with 3 m diameter to accelerate the descent).

The information base for triggering these actions is increasing with mission progress. After separation from Cassini on 25. December 2004 only the alarm clocks are activated in order to properly initialize the instruments for a warm-up phase two hours before the entry starts. At the entry phase the only sensors providing measurements are the accelerometers. In this phase the Titan arrival velocity of about 6 km/s is reduced by friction with the atmospheric particles within 3 minutes to 400 m/s (which corresponds to Mach 1.5), an appropriate velocity for parachute deployment. This deployment velocity is very crucial, as at a too high velocity the parachute will be destroyed, while at a too low velocity the parachute will not inflate. Another crucial parameter is the deployment altitude: only after heat shield jettison, there is direct contact of scientific instruments with the Titan environment and only then scientific measurements will start. Then additional data on pressure are collected and from atmospheric models, conclusions about altitude can be derived. From an altitude of about 45 km also radar altimeter measurements become available and can be used to predict the duration until surface impact. During the 10 year development phases and during the flight, the information about Titan's atmosphere increased and at different stages different control methods to approach these tasks in the most robust way had been discussed (ESA/NASA, 1988; Schilling/Flury, 1990; Patti, 1995; Hassan/Jones, 1997; Clausen, et al, 2002).

4.1 Approach by Expert System Techniques
In the early phases the limited knowledge about the atmosphere demanded more complex control algorithms to compensate the uncertainties. Thus real-time expert system technologies had been analyzed (Ciarlo / Schilling, 1988) for autonomous operations of the Huygens Probe. The overall goal of maximizing the scientific return of the mission had been decomposed into sub-goals, such as optimization of

- descent profiles,
- instrument operation modes,
- energy consumption,
- data transmission,

handled in the so called Scientific Management, as well as failure detection, identification and recovery tasks, dealt with in the Engineering Management.

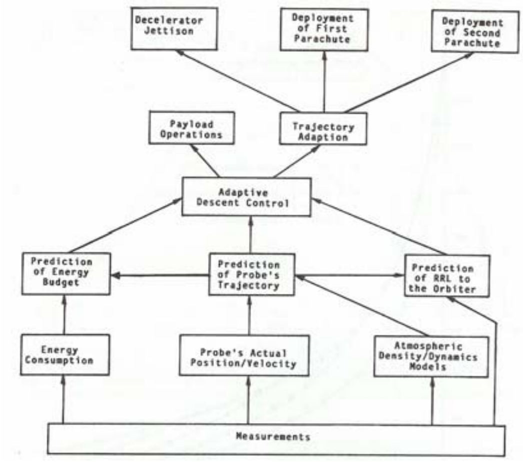

Fig. 8: The information flow in the descent control system .

From these goals major tasks have been derived in order to provide the related inputs for decisions, as by example the determination of Huygens position and velocity, adaptive control of the descent, update of the atmosphere and spacecraft models according to measurements, scheduling of payload operation activities, prediction of remaining resources (energy, data transmission budget). Related methods had to be implemented to provide this inputs in a robust way, most often implemented via functional redundant approaches. Thus this expert system is based on

- facts, such as expected values replaced as soon as possible by measurements, characterized in quality by confidence factors.
- mathematical models, related to Titan ephemeris, atmospheric density profiles, Orbiter and Probe trajectory,
- rules, such as algorithms, empirical relationships, procedures to manipulate the knowledge base to process and draw conclusions from the facts.

These methods had been implemented and tested in simulation and partly hardware-in-the-loop simulation (cf. Fig. 11), but at this stage the storage requirement of about 400 kB was considered at those days as not realizable by radiation hard components.

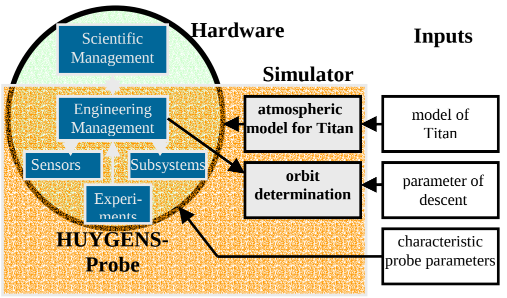

Fig. 9: The simulation setup for the hardware-in-the-loop tests of the expert system approach for Probe operations.

4.2. Adaptive Descent Control

The atmospheric uncertainties with their effects on the descent were anticipated as main challenge for robust data acquisition and transfer. Thus an adaptive descent control system was analyzed (Schilling / Flury, 1990), in order to adapt the models to the measurements in order to improve the prediction of the expected descent profile and to optimize timing of the remaining future control actions on that basis. The atmospheric density ρ can as first approximation be expressed as an exponential function of altitude h:

$$\rho(h) = c_1 \exp(c_2 h)$$

depending on the parameters c_1, c_2 to be updated from measurements. The acceleration due to drag a_D, caused by the friction with atmospheric particles, depends on the Probe's drag coefficient c_D (representing geometric properties of the body), atmospheric density ρ, the Probe's effective cross section area A, the Probe mass m and the Probe velocity v

$$a_D = -0.5\, c_D\, \rho(h)\, A\, v^2 / m$$

Here c_D has been measured in wind channel tests, but as it might have altered during the 7 years of flight under extreme environment conditions, it is considered in that context as another parameter to be adapted. Thus the Probe's trajectory can be predicted from the solution of

$$m\ddot{x} = F_D + F_G$$

with drag force F_D (based on the parameters c_1, c_2, c_D) and the well known gravitational force F_G. Thus in particular from the surface impact prediction, the related link contact period is to be optimized by the suitable timing of control actions. During the descent subsequently more sensors become available. While acceleration a is measured from the first contact with the atmosphere in 1200 km altitude, the atmospheric pressure p can only be measured after heat shield separation at 152 -175 km altitude. Radar altitude measurements become available from an altitude of circa 45 km.

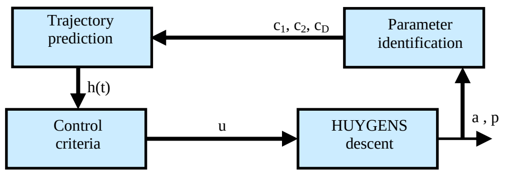

Fig. 10: The schematic for the adaptive descent control.

4.3 The Final Landing Scenario

Due to the change of scenario after the detection of the radio anomaly, described in chapter 3, the Probe delivery was delayed to the third close encounter of Titan. Thus in comparison to the originally planned delivery at first close encounter of Titan, more information became available due to the earlier two fly-bys at 26. October and 13. December 2004. The earlier atmospheric model by Lellouch-Hunten was replaced in 2000 by the Yelle-model, having been confirmed during the two Titan close encounters before Probe delivery. Also a very smooth surface with topographical height variations of less than 150 m was detected. Therefore it was decided to use after this reduction of uncertainties for the descent on 14. January 2005 a simple, fixed timer sequence after parachute deployment. While the parachute deployment was triggered by detection of an acceleration threshold of 10 m/s^2, corresponding to a velocity of Mach 1.5, the heat shield separation was timed 30 s later. The exchange from the large (8 m diameter) towards the small (3 m diameter) parachute occurred 900 s after parachute deployment.

In an altitude of 120 km maximum wind speeds of about 430 km/h were measured from Doppler data. From an altitude of about 60 km the winds calmed down to be very weak near the surface. The Probe descended through haze until about 30 km above surface. After a parachute descent of 148 minutes Huygens landed with an impact velocity of about 20 km/h, settling the Probe with 10 – 15 cm into Titan's surface. After 72 minutes the signal transmission towards Cassini ended, while the Probe's signals were still detected for further 3 hours by Earth based radio telescopes.

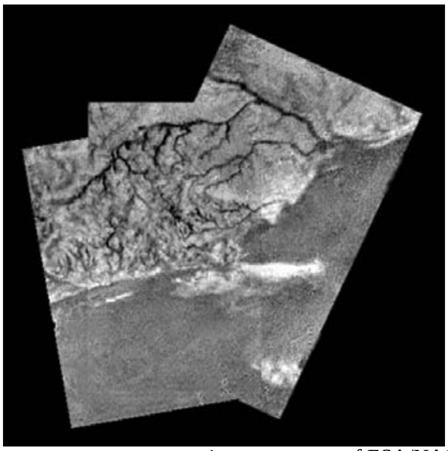

image courtesy of ESA/NASA

Fig. 11: River channel and ridge area of Titan shaped by methane precipitation, imaged at an altitude of 16.2 km (40 m per pixel).

image courtesy of ESA/NASA

Fig.12: The surface of Titan in the near vicinity of the landing point, consisting of a mixture of water and hydrocarbon ice.

5. CONCLUSIONS

Titan is the only moon in the solar system with a dense atmosphere, including significant fractions of Methane and exhibiting exotic chemical reactions. The realization of the Huygens Probe to explore it offered challenging control engineering tasks: The transfer trajectory to Saturn of this largest interplanetary spacecraft so far could only be realized by taking advantage of gravity assisted fly-bys. At a distance as far as Jupiter the radio link problem has been analyzed, the malfunction in the Huygens-Cassini telecommunication link has been identified and strategies for solving the problem have been found. Huygens was the first entry mission implemented by the European Space Agency, offering challenges for autonomous descent control through the only partially known atmosphere of Titan. Despite 7 years in orbit under extreme space conditions, the Huygens-Probe performed perfectly and even survived more than 4 hours on the surface.

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