Control Lessons Learned during the Cassini/Huygens Mission to Explore the Saturnian Moon Titan

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ABSTRACT

Interplanetary spacecraft operations require challenging autonomous reaction capabilities to uncertain environments. Related technology developments in adaptive control and robust information processing strategies offer interesting transfer potential for terrestrial applications, in particular to Unmanned Air Vehicles(UAVs). This paper reviews the technical challenges with emphasis on control engineering aspects at the example of the Huygens atmospheric descent through the uncertain atmosphere of the Saturnian moon Titan, which was successfully realized in January 2005. In the course of the 10 years long development process different approaches to the descent control system had been discussed for the Huygens probe in order to enable a safe landing by parachute on Titan, satisfying given schedule constraints. Remote failure diagnosis is highlighted at the example of a telecommunication link problem detected at the distance of Jupiter. A summary on telecommunications and control features in planetary rovers and pico-satellite formations emphasize further areas of technology transfer potential from space to terrestrial UAV applications.

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Image courtesy of NASA/ESA

Figure 1: Integration of the Cassini / Huygens spacecraft; the persons at the basement provide a reference for size.

1. INTRODUCTION

Interplanetary space missions require a broad range of challenging autonomy capabilities due to operations in uncertain environments at large distances. Related control and information processing approaches offer interesting technology transfer potential for terrestrial applications, including in particular Unmanned Air Vehicles (UAV). Here at the specific example of the Cassini/Huygens (cf. Fig. 1) mission specific autonomy features are discussed related to atmospheric descent and landing on basis of parachutes. Further space vehicle control technologies of interest for the UAV context are summarized in the second part of this contribution, addressing for planetary rovers remote control and navigation, as well as for pico-satellites miniaturisation, formation flying and communication aspects.

In this paper we understand by "autonomy" the capability of a vehicle

- to meet mission performance requirements for a specified period of time without external support,
- to optimise the mission product, e.g. the sensor measurements, within the given constraints.

Main requirements for autonomous reaction capabilities include:

- failure detection, followed by the autonomous initiation of the appropriate fail-safe-mode, such that the spacecraft is not lost before the failure is analysed and recovery actions are initiated from ground,
- increased availability, leading to an improved quality and quantity of the mission product, to be achieved by reduced periods of degraded operation modes,
- re-acquisition of communication links to ground control, in case of disturbances to the radio link.

Specific autonomy challenges for interplanetary missions are raised by

- significant signal transmission delays (in the order of hours),
- no ground control interaction in critical mission phases, like fly-bys or atmospheric descents,
- a structured, but only partly known environment for operations,
- no human interaction capabilities at time critical situations,
- the demand for intelligent, but robust control criteria to be accommodated within the limited resources,
- limited capabilities to verify and test the concepts, as the working conditions can often not be simulated on Earth at a reasonable effort and cost.

For interplanetary spacecrafts it is usually insufficient to provide just reactions leading to a fail-safe-mode, but capabilities are to be implemented to perform nominal functions autonomously and to initiate in case of failures autonomous recovery actions [23].

2. THE HUYGENS MISSION

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. 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). Here specifically approaches are addressed

- to calculate an energy-efficient trajectory in a highly dynamically environment governed by significant non-linearities,
- to perform failure diagnosis and recovery actions at very remote distances,
- to realize an adaptive descent control concept for this most remotely operated UAV.

2.1 The Interplanetary Trajectory

An energy-efficient trajectory is to be calculated taking advantage of the physical environment. 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 [11], [25].

2.1.1 The Fly-By-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 with respect to the planet (cf. Fig. 2).

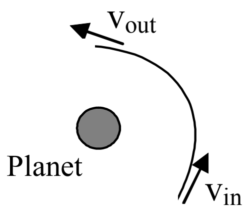

Figure 2: In the reference system of the planet, the spacecraft's incoming velocity vector has the same magnitude as the outgoing velocity vector, but it might change its direction.

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.

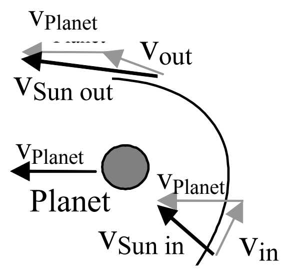

Figure 3: Analyzing the velocities with respect to a solar centric reference system, taking into account the Planet's velocity.

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.[2]).

2.1.2 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. [11]).

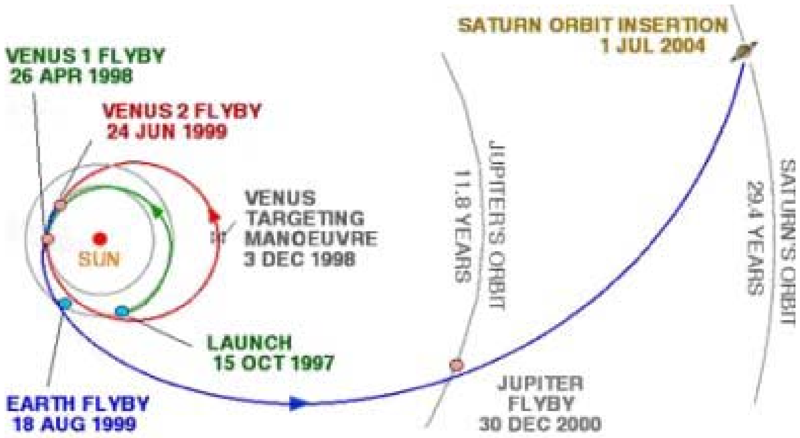

Image courtesy of ESA/NASA

Figure 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.

2.1.3 The Orbit 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 [25].

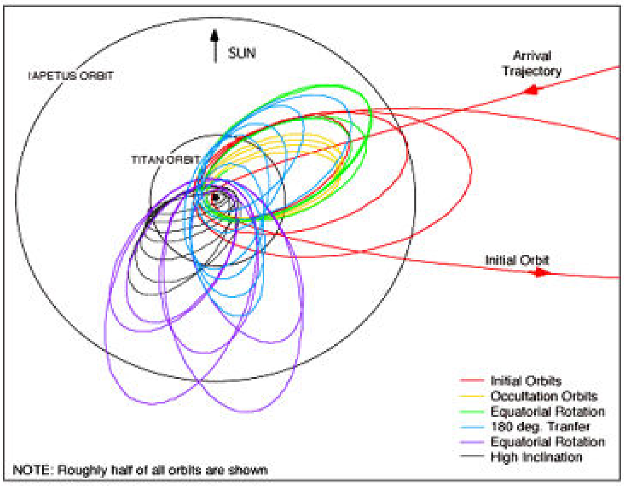

Image courtesy of ESA/NASA

Figure 5: The four-year tour in the Saturnian system 2004 - 2008.

2.2 Tele-Diagnosis of the Radio Link Anomaly

On-flight a failure in the link design from Huygens towards Cassini was detected. This is discussed here as an example for remote failure detection and recovery. 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.

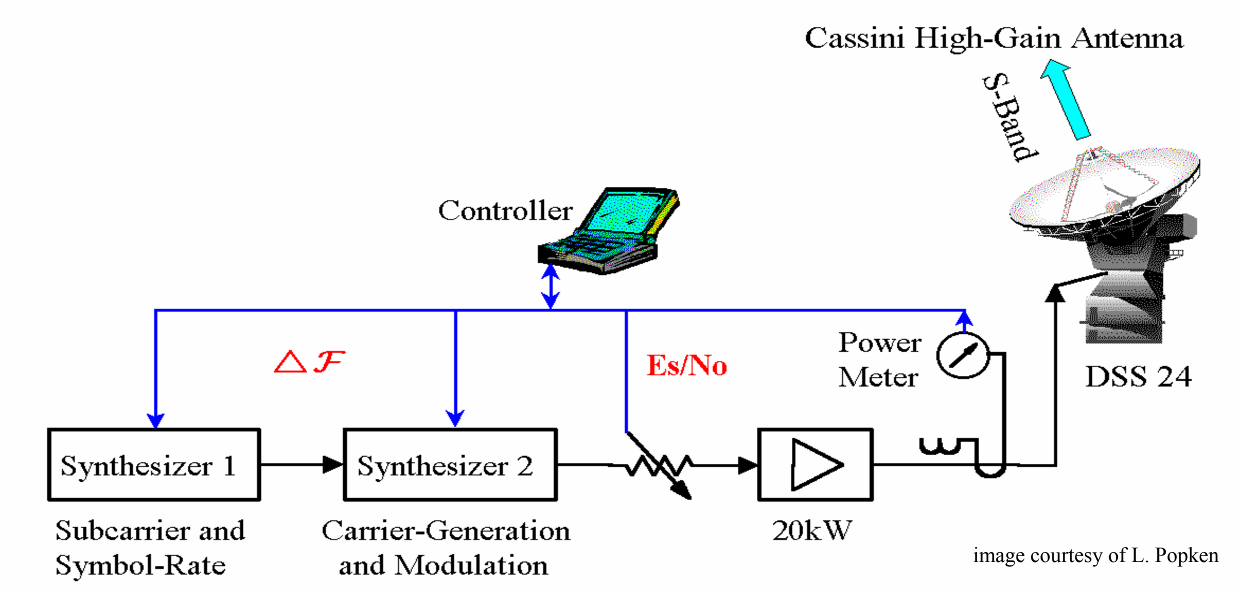

Figure 6: The simulation setup to test the Cassini relay link receiver.

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 [10]. 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.

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.

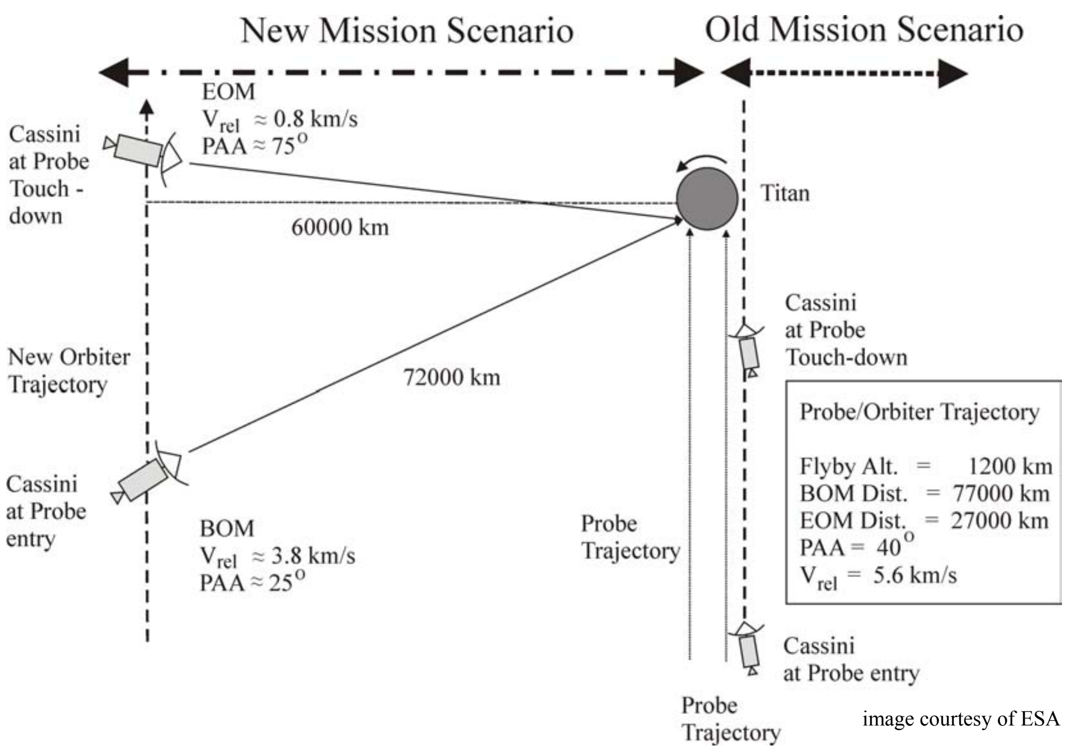

Figure 7: The simulation setup to test the Cassini relay antenna.

2.3 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. [13]). 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 influencing this parachute descent [16].

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 ([5], [6], [13], [10], [7], [4], [19], [16]).

2.3.1 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 [3] 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.

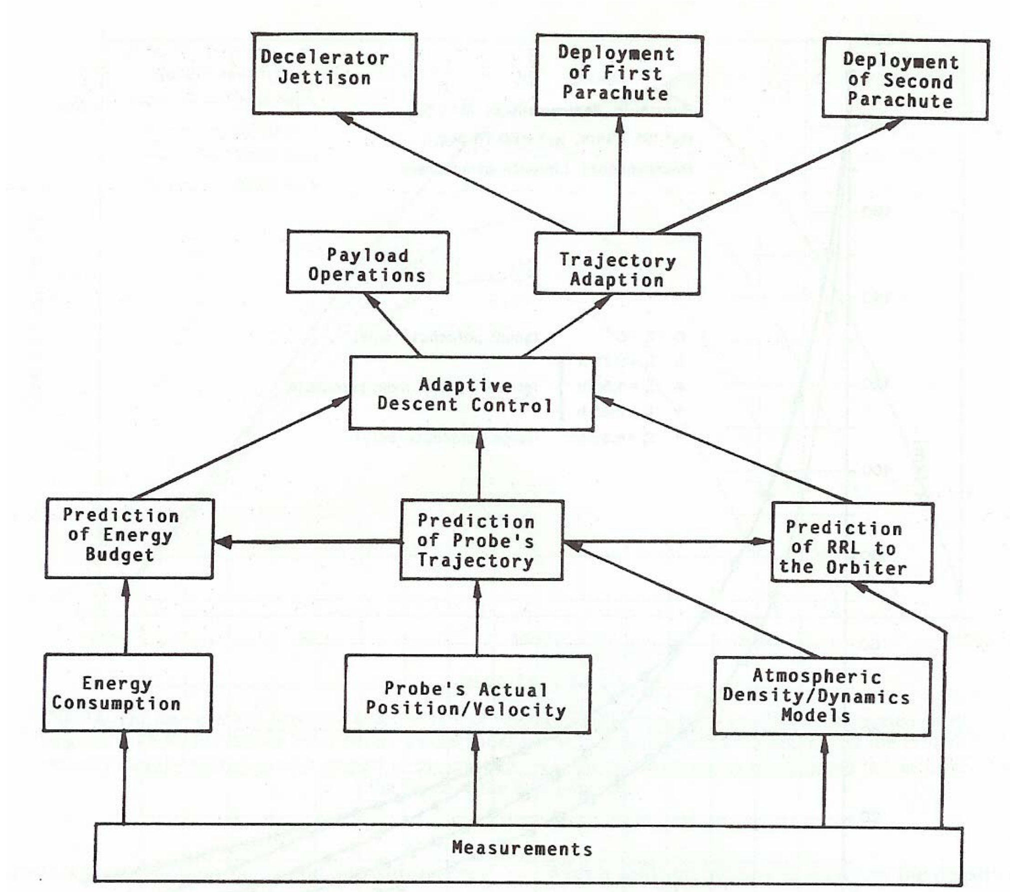

Figure 8: The information flow in the descent control system.

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. 9), but at this stage the storage requirement of about 400 kB was considered at those days as not realizable by radiation hard components.

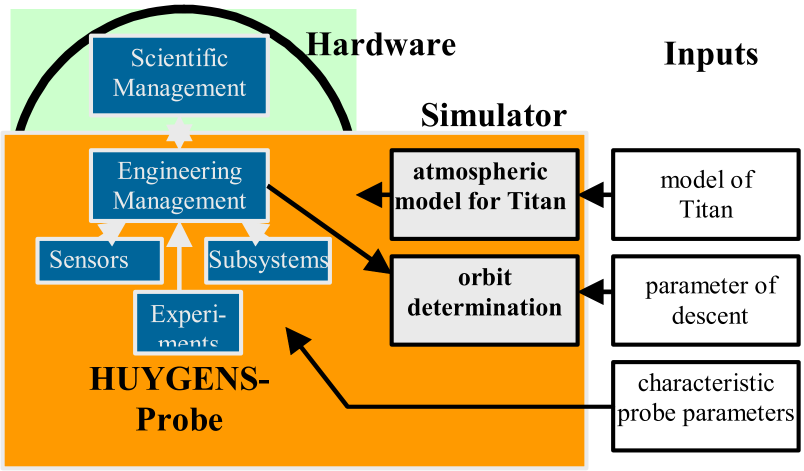

Figure 9: The simulation setup for the hardware-in-the-loop tests of the expert system approach for Probe operations.

2.3.2 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 [13], 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 (surface density), c_2 (height scaling factor) 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.

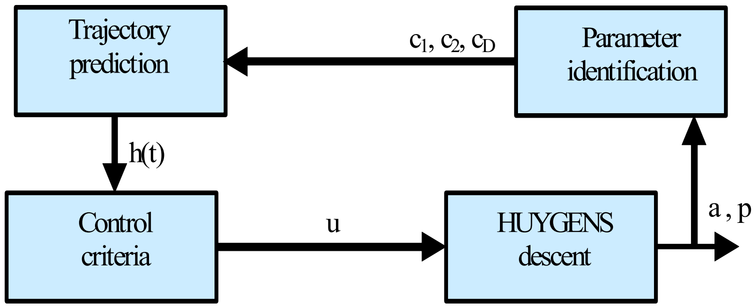

Figure 10: The schematic for the adaptive descent control.

2.3.3 The Final Landing Scenario

Due to the change of scenario after the detection of the radio anomaly, described in chapter 2.2, 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.

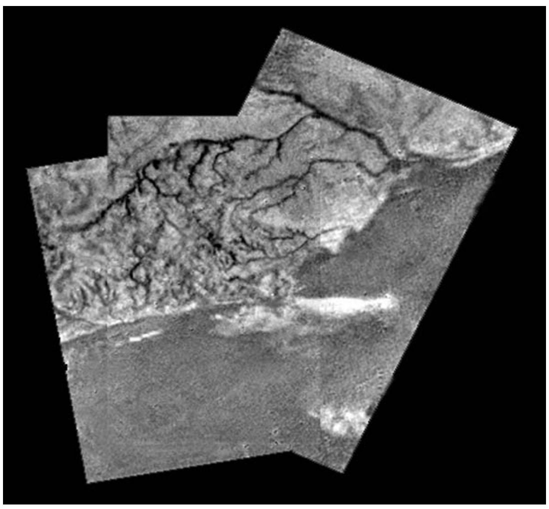

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Figure 11: River channel and ridge area of Titan shaped by methane precipitation, imaged at an altitude of 16.2 km (40 m per pixel).

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

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 2 hours by Earth based radio telescopes.

2.4. Conclusions

The Huygens Probe can be seen as the Unmanned Aerial Vehicle, which has been operated in an atmosphere at the largest distance so far. It has been build to explore the composition of Titan's atmosphere and surface. Due to the huge distance a signal propagation delay of 67 minutes there was no chance for remote control, but all reactions had to be performed autonomously. Thus adaptive control schemes had been implemented to perform parachute descent and landing under time constraints in the uncertain atmosphere of Titan.

To calculate a trajectory to the Saturnian system, highly non-linear dynamic systems had to be solved in order to provide a feasible, energy-efficient path including several swing-by maneuvers. Monitoring the spacecraft health status raised challenging aspects, where as a specific example the remote failure identification and recovery related to the Doppler effect in the telecommunication link between Huygens Probe and Cassini Spacecraft has been addressed.

3. THE MARS ROVER MIDD

Mobile robots are key components in planetary exploration in order to characterize properties of surface areas [15], [21]. Planetary rovers can access places of interest identified from remote sensing data for more detailed in-situ investigation. Technically, rovers raise challenging autonomy requirements in the areas of navigation, including localisation and obstacle avoidance aspects [14]. Mobile vehicles can significantly increase the quality of the characterisation of surface areas, as they allow

- to perform measurements at several locations to calibrate remote sensing data,
- to directly approach specific, interesting targets for measurements,
- to adaptively select new targets according to the results of earlier measurements.

Figure 13: Planetary rovers from the US (on the left Sojourner), Russia (Marsokhod in the rear right), and Europe (MIDD in front right) at the `International Conference on Mobile Planetary Robots´ (Santa Monica , February 1997).

In case of Mars Rover scenarios, the aim of the rover operations concept is to combine autonomous functions on-board the vehicle and teleoperations capabilities of the ground control centre to deal in the most efficient way with the specific challenges of interplanetary missions, such as

- significant signal propagation delays (varying for Mars between 4 and 21 minutes one-way),
- periods without contact (due to the Mars and Earth spin, to limitations in ground station availability, to the orbit geometry of a potential relay satellite)
- only partially known characteristics of the working environment on the other planet.

The European Mars Rover development for a Mobile Instrument Deployment Device (MIDD) was focussing on a small mobile platform (mass 3 kg), to provide mobility in a near range of 20 m at the landing location for about 200 days [17], [18]. The limited radius of activity for such Micro-Rovers permits a lower level of on-board autonomy, compared to vehicles developed to cross distances in the order of several km.

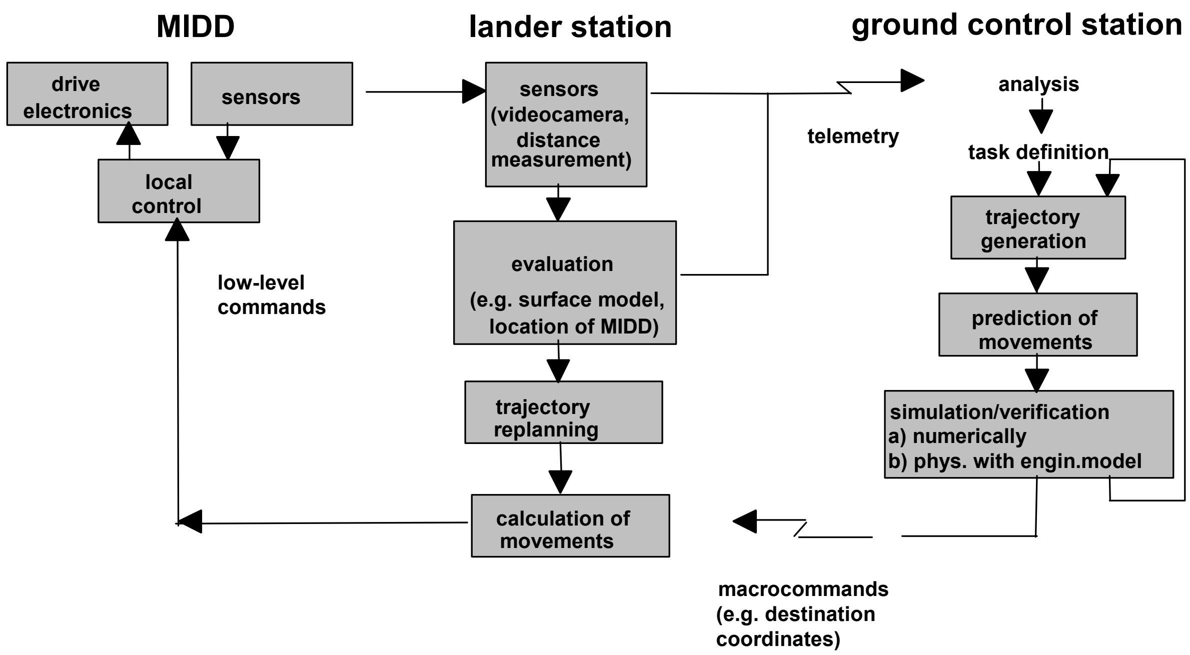

Figure 14: Sharing of operational tasks between ground control, Lander station and Micro-Rover MIDD (Mobile Instrument Deployment Device)

Nevertheless, autonomous execution of high level commands is still the only way of effective remote operations [23], [17]. This requires adaptability of the vehicles to the local terrain and automatic survival strategies in case of unexpected situations or of interrupts in communication contact. The reliable tether link to the lander station, offers access to its data processing and data storage resources. Thus on-board the rover mainly the sensors to characterise the state of the vehicle are placed, while data processing is performed on the lander (cf. Figure 14).

Based on images (from 2 cameras on-board the lander station and one camera on the rover, cf. Figure 15) and other scientific data, operations are planned with the help of simulation and visualisation tools. Based on 3D-visualisation in the ground control centre, problems can be detected and solutions elaborated. Proposed procedures are checked by simulations of the physical and dynamical characteristics of the vehicle. Then related macro-commands are generated, describing high level tasks, such as "go to location (x,y)" or "take a close up image of rock #3", and will be sent to the landing module. After some pre-processing, lower level commands are transmitted from the Lander station to the vehicle on-board control system. Vehicle sensor data are sent to the landing module, closing a local control loop at the remote site. Also navigation is performed in an interactive mode between the vehicle and the landing module. Small deviations (by example due to slightly different mechanical friction coefficients) will be detected and directly corrected on Mars, while more significant deviations (like significant changes in orientation due to slipping at a rock) lead to a stop in order to wait for corrective actions from ground control.

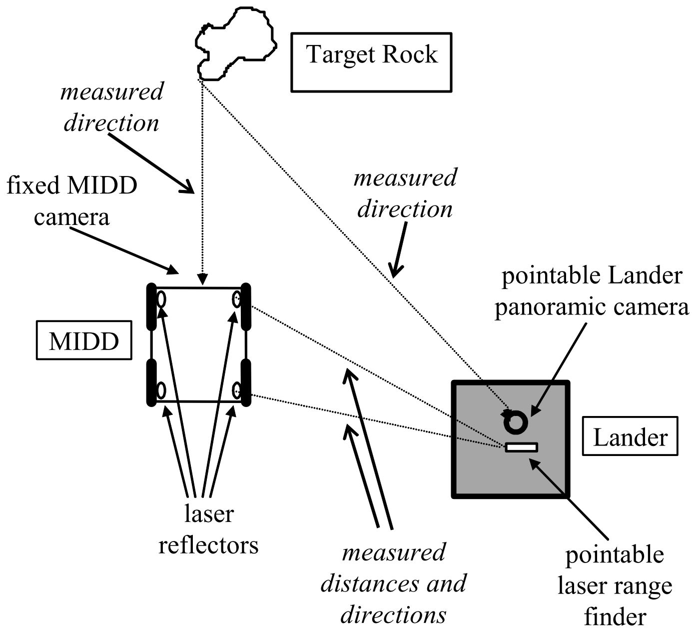

Figure 15: The relative navigation based on reflectors, a laser and cameras on-board rover and lander.

The navigation system involves the methods for determining position, course, and distance travelled. In the framework of the rover-mission this subsystem performs the following essential functions:

- to reach specified targets for instrument deployment,
- to provide the appropriate orientation for imaging,
- to position the scientific instruments appropriately for measurements,
- to avoid conflicts with the tether during motion,
- to enable a return to the Lander.

Here mainly relative navigation towards targets is demanded: In order to plan a path to a target the relative distance and direction is to be determined. A typical situation is represented in Fig.15. The rover MIDD is pointing with its fixed camera towards the target. The laser ranging system and the camera on the Lander scan in the direction of the MIDD, to receive the signals from reflector stripes, placed in the rear and the front of the MIDD. As the distances between reflectors are known, by triangulation methods the location and orientation of the MIDD in relation to the Lander can be derived. On that basis together with the camera pointing direction towards the target again by triangulation the relative distance between MIDD and target is calculated.

Micro-rovers offer a particularly suitable area for technology developments with a high technology spin-off potential for industrial applications. Rather obvious are the similarities in functional requirements for industrial inspection and transport robots. Such tasks for space as well as industrial applications regarding mobile robots are :

- navigation in only partially known terrain (incomplete characterisation of the environment by the sensorics)
- autonomous avoidance of obstacles and dangerous areas
- docking to given targets (objects for scientific measurements respectively material transfer points)
- teleoperations, telemaintenance and telediagnosis of remote machines

Thus robust control strategies to enable reliable operations despite significant signal transmission delays and interruption in ground contacts are also of interest for tele-servicing. The limited bandwidth, availability and the noise in case of terrestrial low-cost telecommunication links imposes similar problems as in planetary exploration. The technology transfer for remote operations technology applied to the servicing of industrial plants is related to the following areas :

- telediagnosis of malfunctions,
- telemaintenance of machines,
- telemonitoring of remote sites by sensors and
- teleoperations of remote equipment including robots.

Thus the need for service personal to visit the industrial plant could be reduced and engineers with experiences in the necessary different engineering disciplines could be concentrated at central locations.

4. THE PICO-SATELLITE UWE-1

Modern miniaturization techniques can significantly contribute to reduce the mass of satellites and thus to minimize the related launch costs. Extreme examples are provided by pico-satellites, where despite a limited mass of 1 kg nevertheless a fully functional space vehicle is to be realized [24], [20]. Related severe limitations on payload mass and volume result, too, limiting achievable resolutions from a single satellite. But interesting experiments can be performed, when data from multiple satellites are combined to derive appropriate resolutions by data post-processing via sensor fusion techniques.

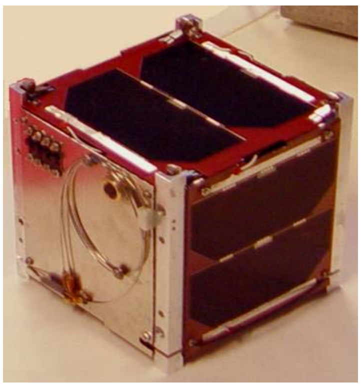

Figure 16: The UWE-1 satellite in storage configuration with one of the two antennas wrapped around on the connector panel, all other side panels are equipped with 2 GaAs solar cells.

As a precursor experiment in this context, the pico-satellite UWE-1 (University Würzburg's Experimental satellite) was realized 2004/2005 and launched into orbit on 27. October 2005 from Plesetzk (Russia) together with 5 companion satellites on a Cosmos 3M rocket. Main objectives of the UWE-1 mission were:

- Adaptation of parameters in internet protocols for the telecommunication link to delays, interruptions and disturbances, typical for space environments
- Technology Development Tests
  - Demonstration of modern miniaturization techniques to implement of fully functional satellite at a mass below 1 kg ,
  - Use of µ-Linux as on-board operating system,
  - In-orbit tests of highly efficient, triple-junction GaAs solar cells, manufactured in Europe,
  - Implementation of a ground control station and integrating it into a international network of CubeSat ground stations via Internet.

Due to the main scientific experiment in telecommunication [22], the payload consisted in that case just of software implemented in the on-board data handling subsystem, based on an energy-efficient H8 micro-processor and µC-Linux as operating system. Thus an appropriate implementation of the IP protocol based on AX25 was realized.

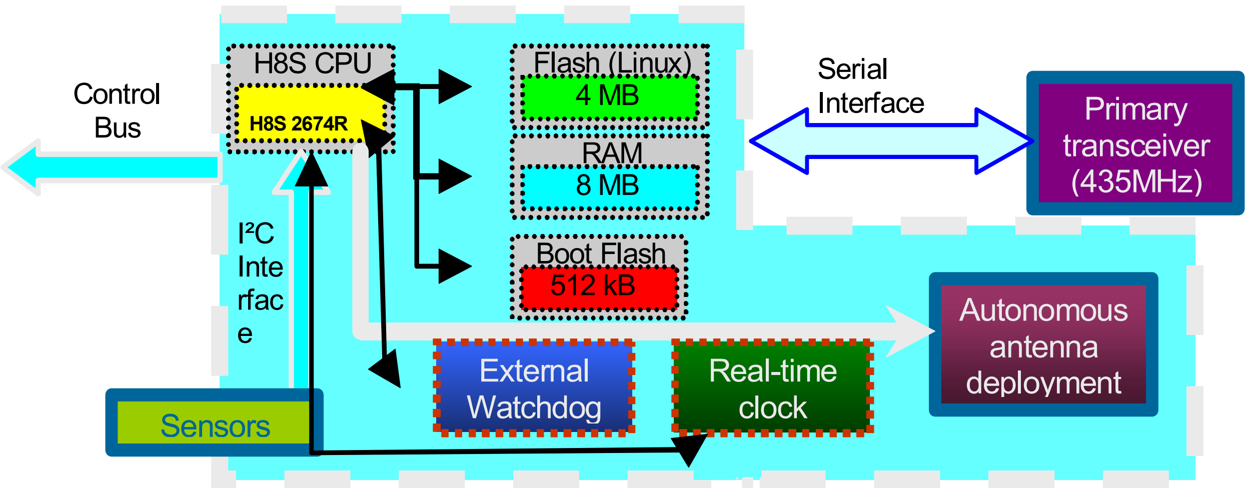

Figure 17: The UWE-1 electrical system architecture

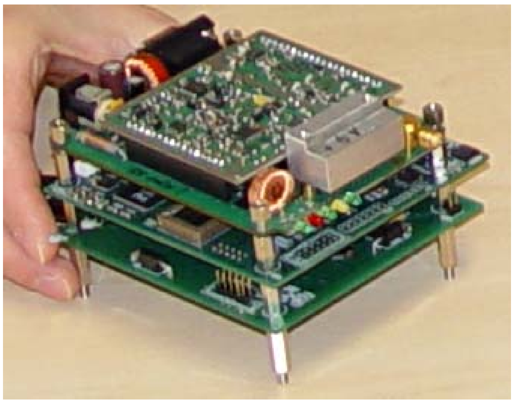

Figure 18: The UWE-1 interior: from top to bottom the transceiver board, the data handling board, and the power system board.

A network of ground control stations was organized to collect data and to forward them via internet to the central node in Würzburg. This way significant experience was acquired in order to realize in the future integrated heterogeneous networks, including swarms of small satellites an interconnected multiple ground stations (cf. Fig. 19) on basis of internet technologies. Specific challenges relate to signal propagation delays, deterministic ones due to the large distances towards the satellites in orbit and stochastic ones due to the terrestrial internet traffic, as well as varying noise levels and link interruptions related to the orbit geometry. Future pico-satellite missions are prepared to further advance the related crucial technologies in miniaturisation, robust telecommunication on basis of internet protocols, setup of coordinated efficient ground control networks, satellite attitude determination and control.

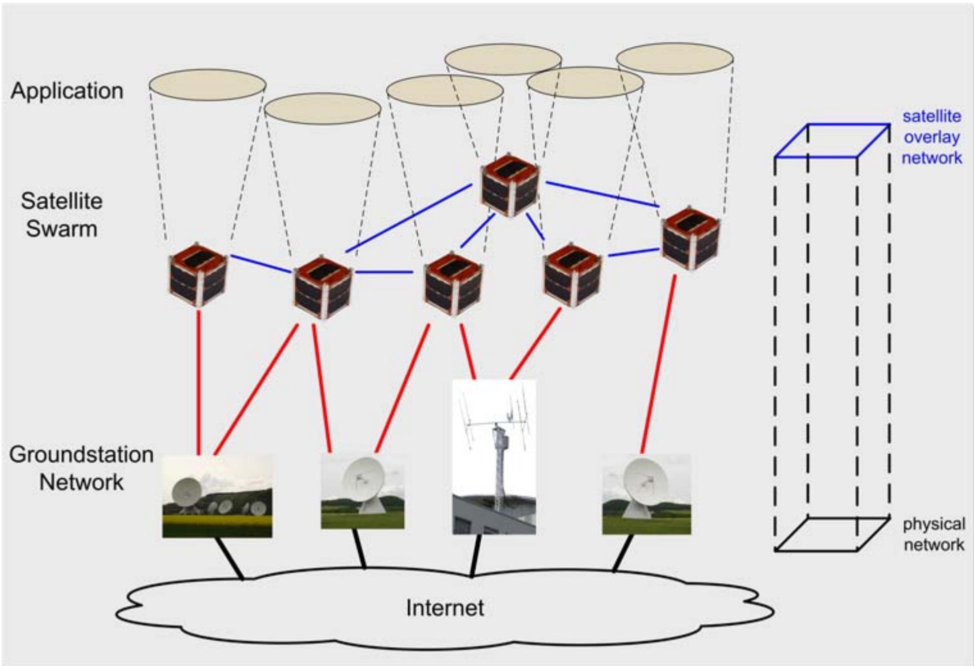

Figure 19: Information flow in the planned heterogeneous network of satellites and ground stations for Earth observation purposes.

5. CONCLUSIONS

Space missions and Unmanned Air Vehicles share similar key technology requirements related to autonomous reaction capabilities, miniaturization of components, reliable communication links, integration of the instruments from several vehicles to a robust sensor network, as well as a need for efficient mission planning and tele-operation approaches. At the specific example of the Cassini/Huygens mission, Mars rovers and pico-satellites related space technologies have been addressed, offering interesting technology transfer potential in these areas.

In particular the autonomous atmospheric descent of the Huygens space probe on 14. January 2005 at Titan included several interesting approaches to adaptively and autonomously react to atmospheric uncertainties. But this mission also included interesting approaches to remote diagnosis of failures and for efficient trajectory planning in highly dynamical environments.

At the example of the Mars Rover MIDD tele-operations and navigation features related to complementary land vehicles were addressed. Finally with UWE-1 exemplarily miniaturization techniques to realize the complete functionalities of a spacecraft within a mass limit of 1 kg are highlighted. Transfer of advanced internet technologies to non-standard scenarios with respect to noise levels, interruptions, delays provides robust telecommunication links, which will be further elaborated in the framework of integrated networks of satellite formations and networks of ground control stations.

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