ALGORITHM AND TECHNOLOGY DEVELOPMENT FOR ACTIVE DEBRIS REMOVAL AT THE INSTITUTE OF SPACE SYSTEMS

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Abstract

To protect functioning satellites and manned vehicles as well as to prevent a cascade effect which might render the Low Earth Orbit (LEO) region unusable in the future, means of analyzing the space debris environment and removing high risk objects are necessary. Having a long heritage in the analysis and simulation of the debris environment with several in-house software tools (e.g. MASTER and PROOF), the Institute of Space Systems (IRAS) is currently expanding its expertise through the formation of a satellite technology workgroup, with the goal of closing the gap between expert knowledge in space debris assessment and technology development for active debris removal (ADR) and space situational awareness. The satellite technology group is applying hands on knowledge and technical knowhow to hardware component and mechanism development to actively make space a safer place. This paper introduces the new core research fields, the interconnection between them, as well as the research infrastructure at IRAS. The research areas include system reliability, system design, guidance, navigation and control (GNC) algorithms for far and close range proximity operations, docking strategies, and docking mechanisms based on smart materials, and detumbling operations.

ABBREVIATIONS

ADR	Active Debris Removal
BeoCube	Braunschweig Educational Operational CubeSat
BePod	Braunschweig Experimental Precise Orbit Determination
COTS	Commercial Off-the-shelf
CW	Clohessy Wiltshire
DIFFRACT	De-Orbit, Formation Flight and Re-Entry Analytical Toolbox
ERIG	Experimental Raumfahrt Interessen Gemeinschaft e.V
FFF	Fused Filament Fabrication
GNC	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
IRAS	Institute of Space Systems
ISS	International Space Station
LEO	Low Earth Orbit
LRR	Laser Retro Reflector
LTI	Linear Time-Invariant
LVLH	Local-Vertical Local-Horizontal
MPC	Model Predictive Control
OOS	On-Orbit Servicing
QuSAD	SQL-Based CubeSat Analysis and Design Tool
ROE	Relative Orbital Element
SCC	Satellite Control Center
SDM	Space Debris Mitigation
TRL	Technology Readiness Level

NOMENCLATURE

x_k	State vector at time k
u_k	Input vector at time k
$\boldsymbol{R}^n$	Set of real vector of n elements
n_x	Dimension of state vector
n_u	dimension of input vector
A	State transition matrix
B	Input transition matrix
$x(0)$	Estimate of current state
$\hat{x}$	Predicted state vector
$\hat{u}$	Computed input vector
$l(\cdot,\cdot)$	Stage cost function
$P(\cdot)$	Terminal cost function
X	State constraint set
U	Input constraint set
X_f	Terminal state constraint set
N	Prediction horizon

1. INTRODUCTION

Sixty years of space activity leave their traces. The successful and failed attempts to bring objects into orbit have something in common: they both generate space junk on a long term. Broken or disused satellites, depleted rocket upper stages, and fragments generated by explosions or collisions are constantly orbiting the Earth. The population of these objects together with a variety of solid body of natural origins, such as micrometeorites, asteroids, and dust is called space debris.

Meanwhile the increasing number of space debris is liable to compromise current and future missions. It became obvious that a substantial research effort has to be done to achieve a deeper understanding of the origins, behavior and dynamics of space debris. The basis of this research is the knowledge and application of general and higher orbital

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mechanics to the space debris population and thus achieving orbit survey, orbit and re-entry prediction, and long term analysis of the space debris environment. The Institute of Space Systems (IRAS) at the Technische Universität Braunschweig belongs to the leading experts in this field. Its research areas include: space debris observation, modelling of individual sources, simulation of fragmentation events, long term analysis, and risk analysis.

With about 2500 tons of material in LEO, collision dynamics can cause a chain reaction that might render entire Orbit regions unusable. The space debris environment will therefore continue growing even in case of the suspension of all human space activities. Currently, many studies are focusing on how to stabilize the LEO space debris environment. Simulations conducted by IRAS show that objects have to be removed actively in order to reach the goal of slowing down the increase or completely reversing the generation of new fragments [1]. Such elaborate and costly missions have to be planned carefully to fulfill their purpose and should not generate new debris in case of unexpected failure.

Additionally to accurate and valid models, space debris research focusses on the development of an effective and cost-efficient ADR technology. In this context, the satellite technology group at IRAS is working on the development and testing of ADR technology with the long term objective of developing affordable technical solutions to the ADR issue with high technology readiness level (TRL). This paper presents the scope of work, its achieved and planned milestones on the way to achieve this goal.

2. RESEARCH STRUCTURE AND STRATEGY

The satellite technology group aims at the extension of the upstream and basic research heritage in space debris modelling and simulation to applied research on active debris removal. Using IRAS long year expertise in space debris, the group identifies innovative key technologies for active debris removal and works on proving its relevance and subsequently achieving high TRL. The conducted activities cover decisive areas for a successful ADR mission design and include:

- System reliability and system design
- GNC for far and close range proximity operations
- Docking strategies and mechanisms based on smart materials
- De-tumbling and re-entry
- CubeSat development and operation

To achieve advanced TRL, it is necessary to demonstrate critical functions of the developed technology and evaluate its performance in a relevant environment. In this context several experimental environments such as an air-bearing table, a sounding rocket testbed or a receiving station are currently operational or under construction (cf. section 5).

Figure 1 depicts IRAS research portfolio in terms of TRL and volume of resources. The group is applying hands on knowledge and technical knowhow to hardware component and algorithm development. By achieving proofs of concepts and demonstrations, IRAS is extracting the best long term innovative ideas from upstream research and accelerating its maturation process to actively make space a safer place in near future.

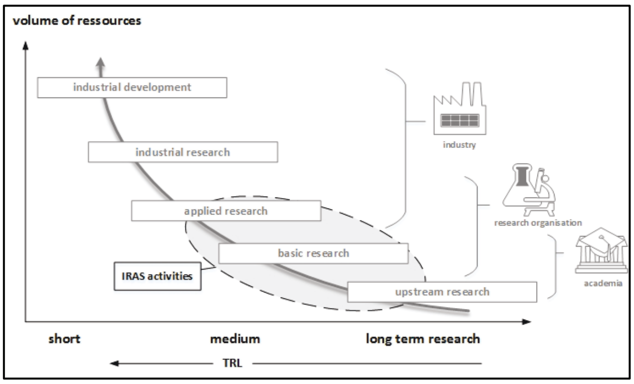

Figure 1: Classification of the actual IRAS research portfolio

3. SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

3.1. Docking Mechanism

During many space missions, the need can arise to connect to spacecraft, for example during ISS re-supply or satellite servicing missions (Space Shuttle and Hubble Space Telescope). Connection can be achieved through either docking or berthing and several mechanisms exist for both cases. As challenging as this task is, it gets even more challenging when one of the spacecraft is non-cooperative. This is for example the case in Active Debris Removal (ADR) or On-Orbit Servicing (OOS) missions, in which a so-called chaser spacecraft needs to approach a non-functional or reduced-functional target spacecraft. Such a mechanism needs to counteract potential misalignments even more than a conventional mechanism. Mechanisms that are currently under research usually employ robotic arms or grippers and clamping mechanisms. IRAS is pursuing a different approach based on gecko-inspired dry adhesives. Those materials adhere through van der Waals forces and can be used in a mechanism. The adhesives have been shown to work well on a variety of materials used in space flight and under space conditions. IRAS has analyzed different adhesives and investigated potential solutions of such mechanisms.

To test small patches of adhesives, a one-dimensional test environment has been set up, as described in [2, 3]. With this test setup, it was shown that adhesive force per area decreases with increasing area of the adhesive pad, and that alignment of the adhesive pad is very critical, as otherwise only small fractions of the adhesive's microstructures get in contact with the counterpart surface.

In further tests with a two-dimensional test environment, a potential mechanism prototype consisting of different tiles, as shown in Figure 2 was tested. The mechanism was mostly manufactured using Fused Filament Fabrication (FFF) as well as commercial-off-the-shelf (COTS) parts. This rapid prototyping approach allows fast and cheap analyses of new concepts. With the 2-D test setup, the influence of for example target curvature or the load angle on the adhesion was analyzed.

Simultaneously, a sounding rocket is prepared in the scope of a student experiment as part of the REXUS program. The experiment shall verify the usability of the adhesives in a near space environment.

With the two test setups and the possibility of using FFF, IRAS is now able to boost the development of mechanisms based on gecko adhesives.

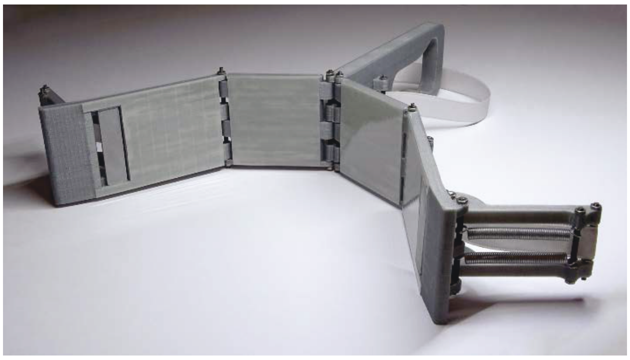

Figure 2: Mechanism prototype based on gecko adhesives, manufactured at IRAS [4]

3.2. Formation Flight and Rendezvous with non-cooperative Targets

To achieve a successful Docking, it is necessary to safely approach the target satellite. This task is particularly challenging in case of non-cooperative targets. Sophisticated algorithms are needed to overcome the relative navigation and collision avoidance issues. IRAS is investigating modern modeling and control techniques which will be described in the following sections.

3.2.1. Parametrization and modelling

Depending on the application area and the needed accuracy several models based on different parameterizations can be used to describe the relative motion of two satellites orbiting the Earth. Nonlinear models are usually used to achieve advanced accuracy needed for proof of concepts. However linear models such as the Clohessy-Wiltshire (CW) equations trade accuracy for simplicity and computation time but still provide good results for close formations. Both approaches are useful and therefore implemented in IRAS Guidance, Navigation and Control (GNC)-Simulator described in section 3.2.3. Figure 3 depicts the mentioned discrepancy between non-linear and linear propagation model for the TanDEM-X /TerraSAR-X formation flight using Two Line Elements (TLE) data from May 24th 2016 04:22:33. The results are generated using IRAS GNC Simulator with an integration time step of 0.1 second [5]. The along track direction is particularly sensitive to uncertainties since it is connected to the condition of bounded relative motion, so that small uncertainties cause a drift of the linearized propagation.

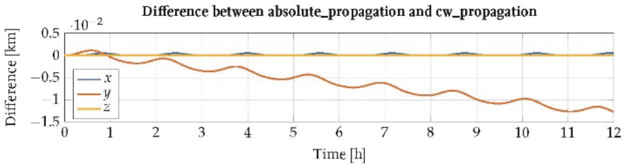

Figure 3: Simulated Discrepancy between non-linear and linear propagation of TanDEM-X and TerraSar-X relative motion using IRAS GNC-Simulator, integration step 0.1 s

The initial condition in form of relative position and velocity in the local-vertical local-horizontal (LVLH) frame are listed in Table 1.

Table 1: initial conditions for the TanDEM-X/TerraSAR-X simulation test case

Relative position		Relative Velocity	
r_x	$0.4326\,km$	v_x	$3.2600 \cdot 10^{-4}\ km/s$
r_y	$4.0571\,km$	v_y	$-9.5842 \cdot 10^{-4}\ km/s$
r_z	$-0.1049\,km$	v_z	$-2.7124 \cdot 10^{-4}\ km/s$

The general equation for motion under the influence of a central force is classically derived in Cartesian parametrization. The equation of relative motion is then obtained by building the difference of two distinct general equations of motion and transforming it into a local orbital frame placed in the target's gravity center, denoted as Hill frame or LVLH-Frame. This parametrization has the disadvantage that for a general orbit, differential equations must be solved in order to obtain the precise relative orbit geometry. Linearizing the aforementioned equations yields the CW equations which in the one hand provide an analytical solution (no integration necessary) but on the other hand are only valid for circular chaser orbits and small relative orbits (linearization assumptions). To overcome these limitations relative orbital elements (ROE) are introduced as described in [6, 7]. These are obtained by using a non-linear combination of Keplerian orbit invariants (no integration necessary) instead of the classical relative positions and velocity initial condition and are valid for arbitrary relative orbits (no linearization). This modern approach provides direct insight into the formation geometry (for collision avoidance) and allows the straightforward adoption of variational equations such as Gauss' to study the effects of orbital perturbations on the relative motion. Both parametrizations are integrated in the GNC-Simulator.

Figure 4 depicts the implementation of the Gauss' variational equations to compute relative orbital maneuvers. Based on Newton's second law the force in LVLH frame is transformed into a velocity increment. The mean argument of latitude is propagated using a linear function depending on mean motion and propagation time. The "relative orbital elements block" then computes the subsequent change in ROE based on the Gauss' variational equations. The propagation is here reduced to one element, the mean argument of latitude, instead of six parameters describing position and velocity. This can be achieved using the described linearized motion or by numerically solving the algebraic Kepler equation without the need of numerical integration. The theory of relative orbital elements and its application is derived in detail in [8].

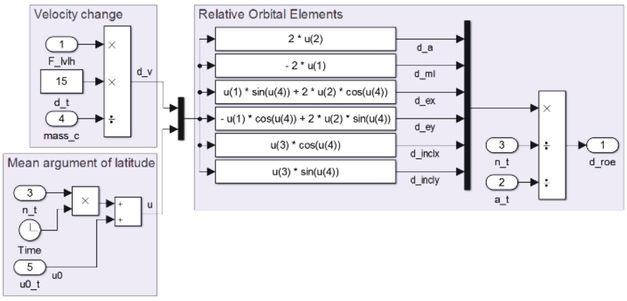

Figure 4: Subsystem of IRAS GNC-Simulator used to compute the change in relative orbital elements induced through a force in the LVLH-Frame

3.2.2. Control

Consider the following discrete-time linear time-invariant (LTI) system:

$$x_{k+1} = Ax_k + Bu_k \tag{1}$$

where $x_k \in \boldsymbol{R}^{n_x}$ and $u_k \in \boldsymbol{R}^{n_u}$ are the state (e.g. position, velocity) and the control input (e.g. thrust), respectively; A is the state transition matrix and B is the control input matrix.

Assume that the estimate $x(0)$ of the current state is available. Let the notations $\hat{x}$ and $\hat{u}$ denote the predicted state and computed input, respectively. Let $l(\hat{x}_i, \hat{u}_i): R^{n_x} \times R^{n_u} \to R$ be the stage cost function and $P(\hat{x}_N): R^{n_x} \to R$ the terminal cost function. Let $X \subseteq R^{n_x}$, $U \subseteq R^{n_u}$ and $X_f \subseteq R^{n_x}$ be the state constraint set, the input constraint set, and the terminal state constraint set, respectively. Let N be the prediction horizon.

The formulation of the classical MPC (i.e. without uncertainties) is as follows. At each sampling instant, the following constrained optimization problem is solved over a finite horizon using the current states as the initial ones:

$$min_{\hat{u}_0,\dots,\hat{u}_{N-1}} J = \sum_{i=0}^{N-1} l(\hat{x}_i, \hat{u}_i) + P(\hat{x}_N) \tag{2a}$$

s. t.

$$\hat{x}_{k+1} = A\hat{x}_k + B\hat{u}_k, k = 0, \dots, N-1 \tag{2b}$$

$$\hat{x}_0 = x(0) \tag{2c}$$

$$\hat{x}_k \in X, k = 0, \dots, N-1 \tag{2d}$$

$$\hat{u}_k \in U, k = 0, \dots, N-1 \tag{2e}$$

$$\hat{x}_N \in X_f. \tag{2f}$$

A control sequence $\{\hat{u}_0, \dots, \hat{u}_{N-1}\}$ is determined and only the first element of this resulting sequence $\hat{u}_0$ is applied to the system.

The cost function J of the constrained optimization problem consists of two parts, the stage cost and the terminal cost. The stage cost $l(\hat{x}_i, \hat{u}_i)$ is to penalize the state errors and the control effort while the terminal cost $P(x_N)$ is an element for establishing the stability of the receding horizon control [9].

The dynamics of the system is regarded as a constraint for both the states and the inputs, as written in (2b). As shown in (2c), the current state $x(0)$ is used as the initial state.

(2d) and (2e) are the state constraint for the system (e.g. the spacecraft in the formation flight are required to keep the relative configuration) and the input constraint (e.g. the thrust of the spacecraft is limited), respectively. The state constraints are soft constraints while the constraint on the input is hard constraints.

Similar to the terminal cost $P(x_N)$, the terminal state constraint (2f) also contributes to the stability of the system [9]. Usually, X_f is chosen as the maximal positive control invariant set [10].

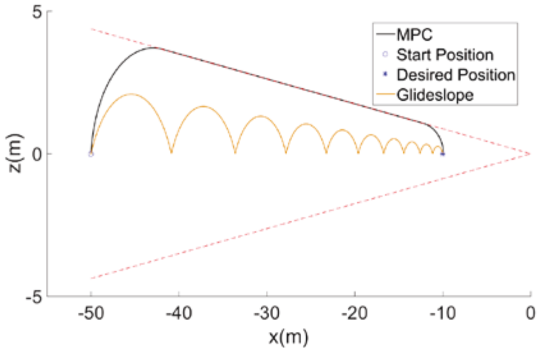

Figure 5: Final Approach Trajectories using MPC and Glideslope Approach

Figure 5 shows the simulation results of a 2-D final approach of the chaser using MPC and glideslope approach.

The chaser and the target are assumed to be in the same orbit plane at the beginning of the maneuver. The chaser starts from the position of 50 m behind the target in the V-bar. The desired position is 10 m behind the target in the V-bar. No uncertainties and disturbances are considered in the simulation.

Impulsive maneuver is assumed for the chaser using the MPC method, i.e., the input of the chaser is ΔVs. One-norm cost is used as the cost function to better consider the fuel cost of the impulsive maneuver. The chaser is required to be stay in the visibility cone during its approach to the target. The half angle of the visibility cone is 5°. The maximal inputs in both directions (i.e., V-bar and R-bar) are 0.1 m/s.

The technique of scaling is used in the problem formulation of MPC in order to make all decision variables of similar magnitudes. The position in the simulation is measured in 10 m while both the velocity and the input expressed in 0.1 m/s.

As shown in Figure 5, in comparison with the trajectory of the glideslope approach (10 impulses are applied here), the trajectory of MPC method is closer to the boundary of the visibility cone. Thus less fuel cost is possible. In fact, the total fuel consumption of MPC for this scenario is 0.0196 m/s while the fuel cost of the glideslope approach is 0.0706 m/s. Figure 6 depicts the input of the chaser using MPC method. With the one-norm cost being the cost function, the input of the chaser is sparse.

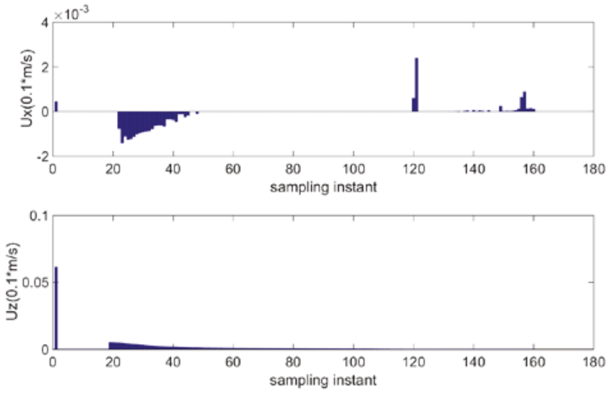

Figure 6: Input of the Chaser using MPC with One-Norm Cost

The ability of MPC to handle the constraints explicitly is at the cost of the extensive computation load as the constrained optimization problem needs to be solved at each sampling time. However, this issue will be solved with the advance in both the speed and the storage capabilities of the computational hardware and active research into more efficient algorithms.

3.2.3. Simulation Environments

- IRAS GNC-Simulator

GNC algorithms and methods are developed and tested in a Matlab/Simulink six degrees of freedom simulation environment [11]. This environment is primarily intended for the evaluation and analysis of the achievable performances via closed-loop simulation of different control and approach strategies. In a further step the simulation environment is planned to be used in combination with the air-bearing table experimental environment described in section 5.1. Matlab has a modular structure and therefore offers tailored “Toolboxes” to specific applications which are to be understood as a collection of functions. An additional product of the software Matlab is Simulink. It is a graphic-oriented software tool to simulate and analyze mathematic models that deal with linear and nonlinear differential equations. In this case, the model is composed of so-called blocks sets which are grouped in different libraries. These models are based on iterative approximation and integration methods such as Runge-Kutta or similar techniques. It is also possible to save created or modified block diagrams in libraries and use those in other models. IRAS GNC-Simulator is basically composed of such a library [5] as depicted in Figure 7 allowing the interconnection of different rotational motion models, perturbation models, translational motion models and animation methods.

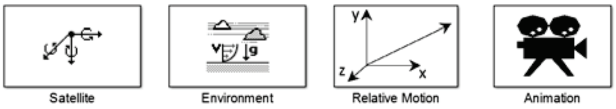

Figure 7: Root level of IRAS GNC-Simulator formation flight *library*

The *Animation 3D* Block from the aerospace blockset allows the animation of a rocket model based on position, velocity and Euler angles and served as a basis for the created IRAS-GNC animation library. The block has been considerably extended and modified using S-functions. An implemented mask allows the selection of several view angles, orbits and Ground track visualization.

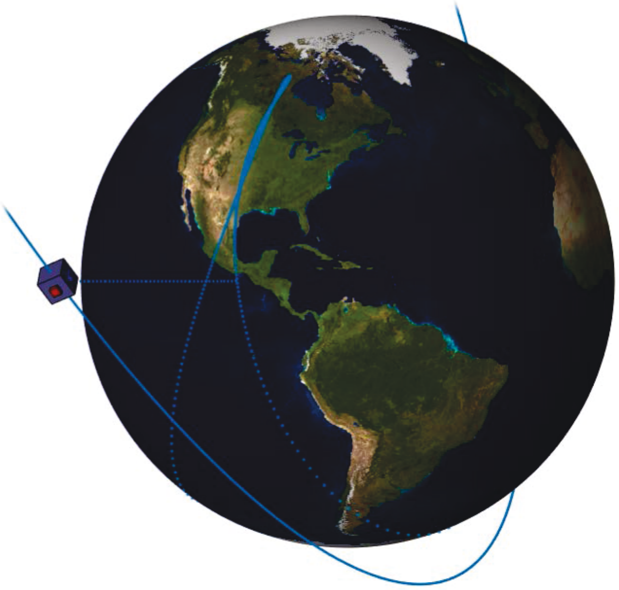

Figure 8: Animated visualization of a Molniya orbit including ground track

- DIFFRACT

De-Orbit, Formation Flight and Re-Entry Analytical Toolbox (DIFFRACT) is as a modular Simulation Environment written in Wolfram Mathematica language. It provides a set of analytical and semi-analytical tools employed for Guidance, Navigation and Control analysis and design of formation flight, rendezvous, docking and de-orbiting of spacecraft in Low Earth Orbit. The Environment is currently under development, the already implemented functionalities include: coordinate transformations, Hohmann transfer computation, maneuver computation and visualization for formation flight, analytical propagation for close formations and Delta-V budget estimation.

4. SATELLITE TECHNOLOGY

In order to develop mature ADR technology it is necessary to develop reliable small satellites which can serve as technology demonstrators. Therefore the satellite technology research performed by IRAS aims to extend the performance and reliability of small satellites using new technology and new methods to enable them for even more complex tasks and scientific missions and assess accurately the reliability and operational lifetime. This research goal is followed by different research programs.

4.1. Next Generation CubeSat Technology

IRAS CubeSat program BeoCube (Braunschweig Educational Operational CubeSat) is the first university CubeSat of the TU Braunschweig and the start of the small satellite program of the Institute of Space Systems. The goal of the program is to educate university students in a hands-on environment and have a platform for technology demonstration. The payload of BeoCube [12] is intended to be BePod – Braunschweig Experimental Precise Orbit Determination – a software-defined Global Navigation Satellite System (GNSS) receiver and Laser Ranging Reflector Experiment to cross-validate the GNSS measurements. The challenge of this project is to fit precise orbit determination into a CubeSat size satellite with its volume, mass, and power constraints. It is necessary to adapt and optimize the algorithm and software code for performance so that it can run on a power consumption optimized CubeSat payload computer. To verify the technology and measurements, a Laser Retro Reflector (LRR) is used, which has to be scaled down to nanosatellite size. It still needs to be proven that the reflective signal is of sufficient quality. Additionally, it is necessary for the laser ranging to have highly accurate propagators and in-track position knowledge below 1 km. Due to standardization and technological advancements in miniaturization CubeSats have become more and more popular and enable space accessibility for a broad community, allowing university students to gain hands-on experience in satellite and space mission design and next generation technology demonstration.

Beside the educational purpose of CubeSats there is a clearly trend over the last years that shows a change in the role of CubeSats from pure educational purpose to perform tasks of usually much bigger satellites. The research program OCULUS which is funded by DLR follows those trend and deals with miniaturization of optical payloads. These are nowadays massive constructions because of their aperture-mirrors. The goal of the research is the development of an aperture with a weight of only a few kilograms instead of hundreds of kilograms. This can be likely achieved using lightweight carbon fibre materials as base structure and apply nano coating, e.g. silver to create a very light mirror. The challenges are the manufacturing accuracies for optical systems creating a sufficiently flat surface. Another problem can arise when coating parabolic surfaces with a continuous layer of a homogenous thickness.

In addition new production methods are investigated. Over the last years the state of the art in miniaturisation, photovoltaic, antenna technology and manufacturing techniques has been dramatically improved. Electronic components (e.g. patch antennas) and solar cells can be printed on heat-resistant flexible substrates, like Kapton, and will have only a thickness of a few micrometres. With such thin film technology it seems possible to enlarge the power generating area significantly, which can enable power critical instruments that are nowadays not feasible. The research focus must lay on foldability, stability and thermal stability of such thin film technology. Another problem is the commercial availability of suitable thin solar cells, the lower efficiency and the interaction with space environment and in orbit demonstration of the technology.

4.2. QuSAD

A SQL-Based CubeSat Analysis and Design Tool (QuSAD) was developed to support the CubeSat development at the Institute of Space Systems at TU Braunschweig (IRAS). This Interactive, Space Mission Analysis, Design, and Simulation Toolkit condenses the necessary knowledge of components, system, mission design, operations, and analysis functionality to find an optimum component combination without exceeding the mission requirements and resources. The toolkit's core module consists of an SQL and a MATLAB segment. The SQL database accommodates currently available Commercial off the Shelf (COTS) CubeSat components. By today it consisting of more than 230 components sorted by subsystems i.g. attitude determination and control system (ADCS), electronic power system (EPS), on-board data handling (OBDH), communication, propulsion, structure, payloads subsystems, and available kit solutions. MySQL has been chosen to enable continuously updates of the increasing the number of manufacturers that offer hardware for CubeSats. An optimum design needs the possibility to choose from a large pool of components while using design analyses methods to evaluate the potential of the design. The MATLAB segment provides the graphical user interface and an extendable modular structure that can connect and interact with the database, accommodate basic tools to assist the design process, analyze trade-off parameters, and evaluate design budgets. The user can interactively select his satellite mission using COTS components from the database and integrate them into a virtual satellite. Subsequently, the design can be analyzed, saved and optimized using the Profile Viewer to assess mass, volume, cost, link, and power budgets. The software provides three main functionalities in the current state: database handling, CubeSat design, and profile viewer (see Figure 9).

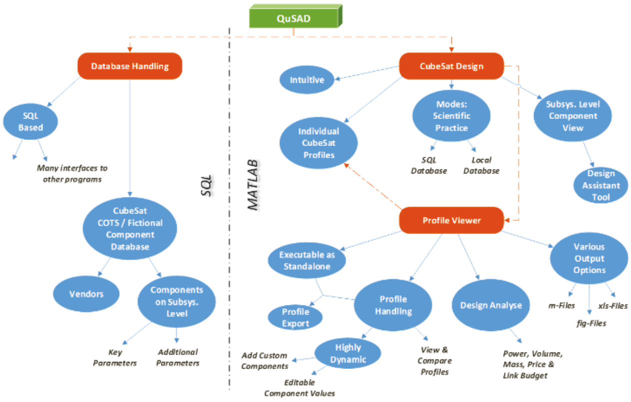

Figure 9: QuSAD current implementation overview

It is intended to extend the tools analyses functionality and continuously maintain and update the COTS database and existing modules. The additional modules can also add or embed complex functionality of existing tools developed at the IRAS. Examples of additional modules are orbit propagation, battery degradation trending, thermal analyses, mission planning according to Space Debris Mitigation (SDM) Guidelines, conjunction analyses, and 3D-Visualization.

4.3. System Reliability

The development of a reliable satellite design is a major concern in modern space industry, especially when considering single satellites for active debris removal or mega-constellations for advanced worldwide telecommunication, earth observation and navigation services. One example for these mega-constellations is the OneWeb mission that consists of 648 satellites at an altitude of 1200 km and a single mass of about 150 kg to provide worldwide WWAN services [13, 14]. A major issue of these huge satellite constellations is the trade-off between the operational reliability and availability of each single satellite system on the one hand and the cost effectiveness of the whole constellation on the other. The failure of a single low cost satellite system can already have a direct influence on the potential performance of a whole satellite constellation and the costs for an unscheduled mission to replace and dispose a degraded satellite are by far higher than the usage of a more reliable medium cost satellite system in first place.

To illustrate this in more detail, Figure 10 shows the qualitative relation between the reliability of a mega-constellations' satellite design and the resulting total mission costs. The ideal constellation mission considers an operation without any satellite failures over the whole mission duration. In this case no further maintenance costs for spare satellites and extra launchers for replacement missions have to be taken into account. In case of extremely short mission durations, this allows the operation of less reliable low cost designs.

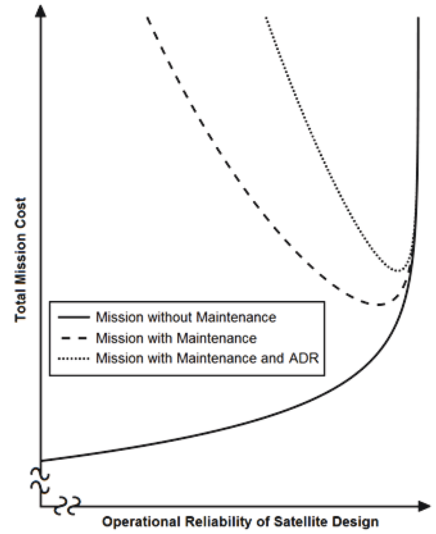

Figure 10: Qualitative estimation of total mission costs for mega-constellations depending on the operational reliability of the chosen satellite design

However, in most probable cases and longer mission durations any unreliable satellite design leads to a high loss of satellites that have to be replaced to maintain the performance of the constellation, which also leads to immense maintenance costs. As a result, more expensive and reliable satellite systems become more attractive to satellite owners than low cost satellite systems. This effect is even amplified in case of planned ADR missions for space debris mitigation because of the extra development and manufacturing of ADR satellites and the purchase of further extra launchers.

To address this trade-off issue, IRAS is developing new methods and tools for the prediction and optimization of single satellites' and mega-constellations' mission reliability and lifecycle costs. The new methods will be based on further advanced reliability methods from modern aviation, automobile and nuclear industry and be adapted to the requirements of space operation. Besides common internal failures (like design or single component failures), the resulting tools will also consider external factors like degradation by solar radiation and thermal fluctuations, impacts of space debris, launch failures as well as the cost factor of insurances and potential ADR missions to deliver far more appropriate system designs to the current space market. By the development of a reliable satellite design, it is also possible to achieve a reduction of cost-intense on-ground tests. Finally, the new approaches will be used to analyze the potential increase of service income and decreasing probability of a successful disposal maneuver by the extension of a satellite's lifetime.

5. RESEARCH INFRASTRUCTURE AND FIRST RESULTS

5.1. Air bearing Table

To achieve advanced TRL for spacecraft subsystems, docking mechanisms as well as GNC techniques, it is necessary to demonstrate critical functions and evaluate its performance in a relevant environment. Often it is sufficient to simulate microgravity to achieve such an objective. This is for example the case if other characteristics of the operational environment such as radiation are proved to be irrelevant. An air-bearing table is currently being set up at IRAS to allow such tests. It is aimed to enable satellite engineering models experience weightlessness by floating them on air cushions and guaranteeing so at least three degrees of freedom (two translational and one rotational). Unlike most of the existing free-floating test environments, where satellite models require separate supply of compressed gas to form an air cushion for themselves, the IRAS air-bearing table itself generates an air cushion to support the satellite models. The models are driven using electric propellers. Thus, long-term simulations are possible. The test environment is currently under construction. The air-bearing table consists of modular aeromechanical platforms with embedded nozzles, which are supported by an aluminum structure. The modular platforms can be actuated separately and thus it is possible to operate only a portion of the table if necessary. The air supply is ensured via a set of ring air blowers driven by electric engines. The modular platforms consume air at a range of pressures and flow rates which depend on the size and weight of the mockups being floated. The modularity in the platform and blower design allow a wide range of sizes and weights. A schematic drawing of the air-bearing table is shown in Figure 11.

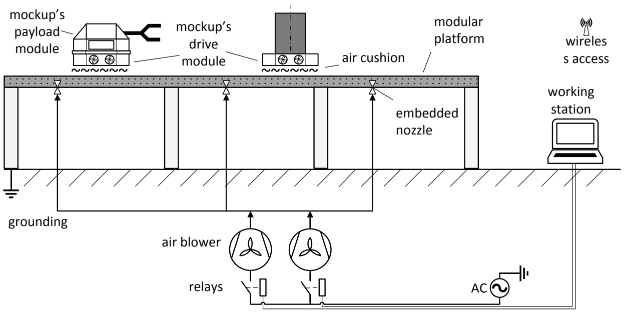

Figure 11: IRAS air-bearing table concept

5.2. Gecko Material Test Facility

To assess the potential of different adhesives, IRAS has set up two test facilities for gecko materials. Those allow on the one hand the basic characterization of the materials' behavior through one-dimensional load tests (1-D test environment), and on the other hand the analysis of mechanism prototypes under different load cases (2-D test environment).
Figure 12 shows the 2-D test environment. With this test environment, typical targets can be simulated. These are for example upper stage rocket bodies with a cylindrical shape in the range of a few meters. In the test environment, an acrylic glass plate is bent to simulate a certain target radius. It has been shown in [4] that the real deflection curve of the acrylic glass comes very close to an idealized circular arc. Thus, the test results should resemble adhesion on a cylindrical target object. With the test environment, it could for example be shown that adhesion is higher on larger radii [4]. For the mechanism shown in Figure 12, the adhesive load is in the range of 15 N.

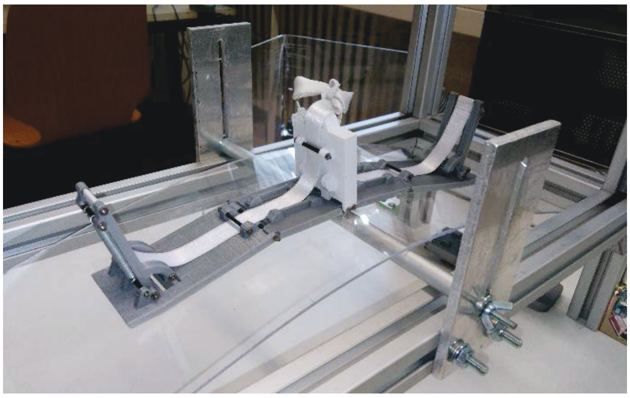

Figure 12: 2-D test environment simulating target radii

Future tests at IRAS shall use the existing test environments to validate further mechanism concepts. This is done in preparation for future tests with the air bearing test bed that is currently implemented at IRAS.

6. SUMMARY AND FUTURE WORK

The satellite technology group is working on the development and testing of ADR technology with the long term objective of developing affordable technical solutions to the ADR issue with high technology readiness level (TRL). Therefore, the conducted activities cover decisive areas for a successful ADR mission design, including reliable satellite design, GNC for range proximity operations, docking strategies and mechanisms based on smart materials as well as CubeSat development and operation.

To achieve advanced TRL, it is necessary to demonstrate critical functions of the developed technology and evaluate its performance in a relevant environment. In this context several simulation and experimental environments such as a 6 DOF simulator, an air-bearing table for dynamic GNC and smart material docking experiments, a sounding rocket experiment for smart material experiments under true space conditions or a receiving station for CubeSat communications are currently under development or in procurement. In case of the docking mechanism research, first quasi-static tests with smart materials have already been carried out successfully and further concept studies will follow. Most of the future hardware studies will be based on rapid prototyping (FFF and COTS) design for cost-efficient fundamental testing environments.

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