APPROACHES AND MODELS FOR FLEXIBLE TETHER CONNECTIONS IN ACTIVE DEBRIS REMOVAL MISSIONS

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ABSTRACT

A tether is a promising solution for an active debris removal (ADR) mission, as it does not need a specific docking interface or linking port as in missions with a robotic arm (rigid link). However, the control and stabilization of the target after capture is much more ambitious due to of the lack of a fixed connection. The target object, an old rocket upper stage or non functional satellite, might rotate or tumble. All maneuvers have to be performed by the chaser; the tether transmits the maneuver signal to the linked target. The aim is a fast stabilization of the target for a safe and secure de-orbiting to avoid for example a collision of the chaser and target in space that will produce a mass of new fragments that may cause additional collisions or fragmentation. Indeed a tether allows the chaser to operate in a higher distance to the target and capturing difficulties through tumbling can be avoid by a net.

At the Institute of Space Systems of the Technische Universität Braunschweig (IRAS) is in cooperation with Airbus Defence and Space Bremen currently a software tool (Tether Dynamics Toolbox - TDT) under development. This Matlab/SIMULINK®Toolbox provides the capability to analyze a tethered ADR mission starting from the initial capture (including the stabilization phase) until the de-orbiting of the ADR system. In the toolbox the flexible tether can be represented by different modeling approaches, e.g. as a flexible bar, lumped mass system or as continuous rope. In dependence on the required analyses the user can switch between these approaches. The paper gives an update on the current development process and road map. Also details of the implemented and planned tether modeling approaches are presented.

Key words: Tethered Space Systems, Active Debris Removal.

1. INTRODUCTION

This paper gives an update on the development process of the Tether Dynamics Toolbox (TDT) at the Institute of Space Systems - TU Braunschweig (IRAS). The use of tethered space systems for active debris removal issues is a much-considered approach, especially in the combination with a harpoon or net. One example is the "RemoveDebris" Mission that might be launched and operated in 2017. In this mission, it is planned to capture a released Cube Sat using a tethered net and to shoot a tethered harpoon through a demo plate. [1]. Other examples are the performed MIT SPHERES tether experiments in late 2016 and early 2017 during SPHERES test session 85 and 88 [2].

One of the key aspects of a tethered ADR mission is the dynamic of the tether and its influence on the attached spacecraft. During an ADR mission normally one non-operational target is captured by an operated capture vehicle (chaser). These missions need to focus on safety, so a safe and secure de-orbiting is required. Among others, it is necessary to prevent collision between the captured target and the towing chaser. To ensure the safety of an ADR mission an, active control of the Tethered Space System (TSpS) is required. Therefore, the dynamics and the transmission capabilities of the tether needs to be analyzed and predicted. Each maneuver performed by the chaser has an influence on the flexibly connected target by inducing a tractive power. Thus the TSpS needs to prevent any winding or high oscillation situations where the TSpS becomes uncontrollable

The TDT is a Matlab/SIMULINK® based toolbox that should support users in various use-cases of tethered ADR operations to:

1. Specification of tether parameters (material, diameter, length etc.) in dependence of ADR mission requirements and the environment.
2. Analyse of tether dynamics under consideration of

mission (captured target, chaser de-orbit capabilities), damping effects

3. Evaluation of required tether properties

4. Pre-analysis of occurring instabilities and prevention methods (active damper etc.)

Yet developed tether simulation tools often focuses on a specific mission or task. Normally they have been developed for preliminary concept studies or mission (phases) analysis:

- SKYLINE: Developed at the beginning of the 90s the tether simulation tool SKYLINE was developed to analyze the deployment phase of long tethers. Therefore effects like oscillations and aerodynamic drag have been considered. Algorithms and control procedures for the deployed tether or the TSS are not included in this tool. [6]
- YESSim: This tool is specifically developed for the European tether mission Yes2 it is an upgraded version of the tool BEASim which models the tether a lump-massed system. Considered are various orbital perturbations. The tool served mainly the design of the eject/retrial and break system for the SEDS-1 and SEDS-2 mission[8].
- STS: The STS simulator was also developed in the 90s to determine algorithms to pull out or roll in the tether. An essential feature of this simulator is the ability to apply external forces on the tether.

An overview of developed and currently used tether software tools is given by Kruijiff[5] and Chen[7]. They describe the specific use cases, modeling approaches and some of the limitations of the tools. Thus ADR missions which represent the flexible coupling of two spacecraft requires a specific simulation environment taking the unique ADR requirements into account. One of the most obvious boundary conditions of ADR missions in comparison to other tether use cases is the connected non-operational or even tumbling target. So it is required to attend the connected end bodies and there back

Towards other simulations and on the market available products, the TDT contains at least three different modeling approaches for tether dynamics. So in dependence of the required results and especially result accuracy analysis can be performed. Another difference is the expected mission duration. After the capture of the target, the chaser starts with its stabilization and de-orbit phase. So the overall mission duration starting from the capture phase is less than 36 h till the TSpS reenter the atmosphere. Also, the total length of ADR tether's is rather short in comparison to other applications (space escalator, elevator) [3, 4]. Thus long term effects and most of the natural perturbations are negligible [9]. Only the earth harmonics and the atmospheric drag (in lower orbit regimes) are considered cause these are the main influences besides the overall thrust of the chaser that is taken into account in a separate maneuver / propagation module For the earth harmonics the EGM2008 and for the atmosphere the NRLMSISE-00 model is implemented in the toolbox.

Another feature of the TDT is the experimental data subsystem. With these sub-module, it is planned to validate the implemented tether models and features. One data source is the performed ISS Tether experiments (SPHERES session 85 and 88). For later it is planned to define and run several test session on the IRAS air bearing table that is presently under construction. The ISS experiments provide a large database. However, it must be considered that the experiments where performed in an atmosphere that has an influence on the absolute data sets. Therefore some research activities in this field are ongoing till this module can be integrated into the TDT. More details, especially on the experiment results will be published soon.

An overview of the architecture and the modules of the TDT are given in figure 1. So the software consists of four main blocks of those are three responsible for the essential function.

- **TSpS Propagation**
  Propagation of the target and chaser under consideration of a flexible connection. The tether is considered via a tether pull back acceleration (TBPA) based on the tether properties and resulting elongation.
- **Tether Dynamic Modeling**
  Represents the included modeling approaches for tethers in space. Each model is included as a separate block and can be selected by the user depending analysis requirements and specific tasks.
- **TSpS Guidance Navigation and Control**
  These module m is responsible for the analysis of the tether motion and dynamics as well as the prediction of stabilization methods and procedures.

The fourth block is created as front- and back-end to interact with the user and to proceed the operations and analyses. A detailed description of the modules and the connection, respectively the dependencies between them is given in [14].

The TDT is currently still under development, this paper gives a comprehensive update on the implemented functionality and the development road-map. To do so, this paper first gives in section 2 an overview of the implemented tether models. Section 3 focuses on the implementation progress and the roadmap while section 4 presents some updated simulation results of the implemented features.

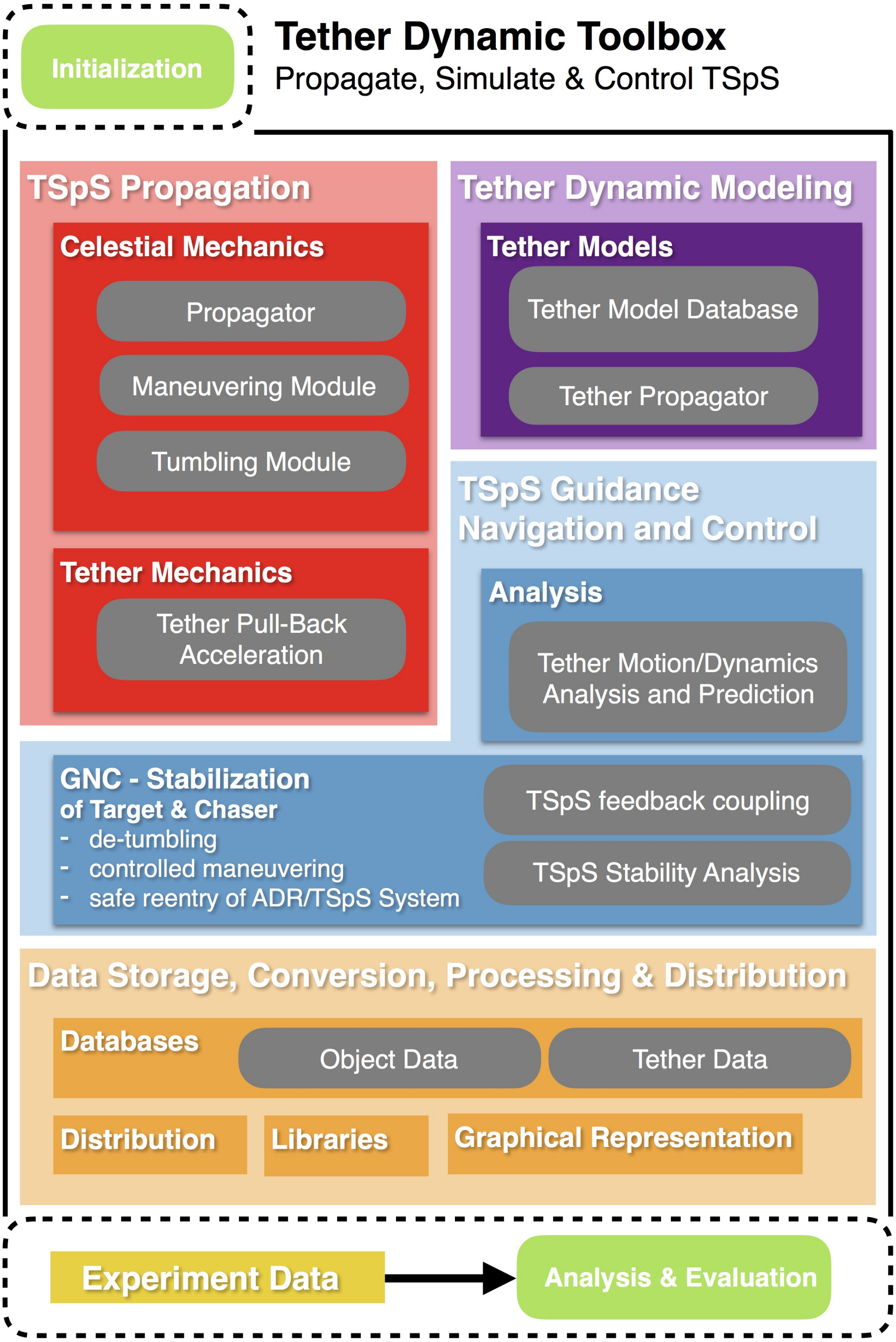

Figure 1. Schematic structure of the Tether Dynamic Toolbox (TD) including sub-blocks [14]

2. TETHER MODELS

Existing tether models can be sorted into three categories, depending on the mathematical or physical approach [11]

1. Bar modeled tether (ponderous/massless, elastic/inelastic)
2. Tether modeled as continuous thread
3. Tether modeled as set of connected elements/visco-elastic bars

When choosing a suitable model, various aspects must be taken into account in addition to the planned application and analysis capability. Thus models of the first category are usually already suitable for first approximations. More complex are models of the second category, which are often represented by nonlinear partial differential equations (PDE). Models from the third category have a more physical approach. Here, the rope is described as a series of mass-spring damper systems (lumped-mass-systems). Figure 2 shows a schematic representation of the different tether category models. The blue arrows represent the connection to the end-bodies (chaser and target), while the green ones represent extraneous disturbances. Depending on the model, this ultimately leads to longitudinal and transverse deflections of the rope. These deflections must then be damped, for example, passively by a damper or by an active engagement of the chaser (firing of thrusters). This active intervention leads inevitably to a change in the orbit that needs to be considered by the overall propagation of the TSpS. The individual categories are described in more detail in the following sub-sections 2.1 till 2.3.

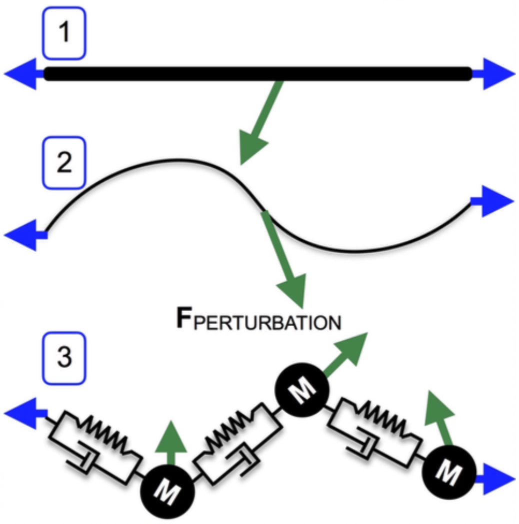

Figure 2. Schematic Representation of tether model categories

The commonality of all models in the TDT is their integration in the overall process in consequence of the modularity of the software. The input for the modules are the positions and accelerations of the connected end-bodies as a boundary condition for the solver. The minimum output is the TPBA (required for the propagation module).

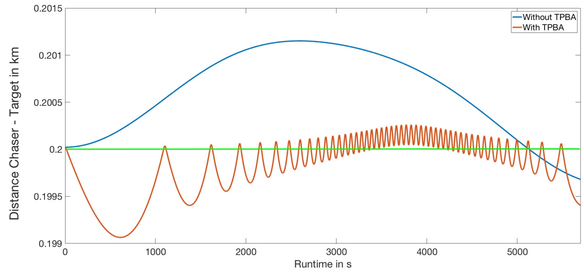

Figure 3. Tether Pull Back Acceleration (TPBA) Propagation Consideration

Figure 3 shows the influence of the TPBA (flexible connection) between the chaser and target for a small eccentric orbit. In these simulation run chaser and target are in the same orbital plane at 800 km altitude and high inclination of 98 deg, the chaser is placed 200 m behind the target. The green line shows marks the initial distance or length of the tether l_0. While the blue line shows the distance between the target and chaser without TPBA and the red one with TPBA. At $t = 0$ the simulation starts in the perigee of the target. Without consideration of the TPBA, the distance increases by up to a factor of 6 compared to the TPBA propagation. This propagation shows a much higher dynamic in the system. Thus, the sequence of regions of elongation and compression is significantly higher, since, after an elongation has taken place, the tether is subsequently pulled together as a result of the TPBA. However, also in this run, a time range with a continuously tensioned tether can be seen. Especially in this time range there is a high alternating frequency. Depending on the configuration of the tether, the frequency and the intensity vary. A detailed analysis of the influences of the tether parameters on the frequency is given in [14].

Thus, depending on the tether model, further data are sent to the data storage/processing block. With active Guidance Navigation and Control (GNC) module an additional data package is generated and yet passive stored. These data package includes some tether data (e.g. elongation rate) and the state of the end bodies. Further analysis can be done in the GNC block after one propagation run of the TSpS. Within one of the next versions it is planned to implement the GNC block right in the loop with active feedback functions to interact with the running simulation. So the influence of a direct change of the e.g. the tether length via a spooling mechanism or a higher damping at the end bodies can be directly analyzed. However, some work still needs to be done till this feature is completely integrated and functional.

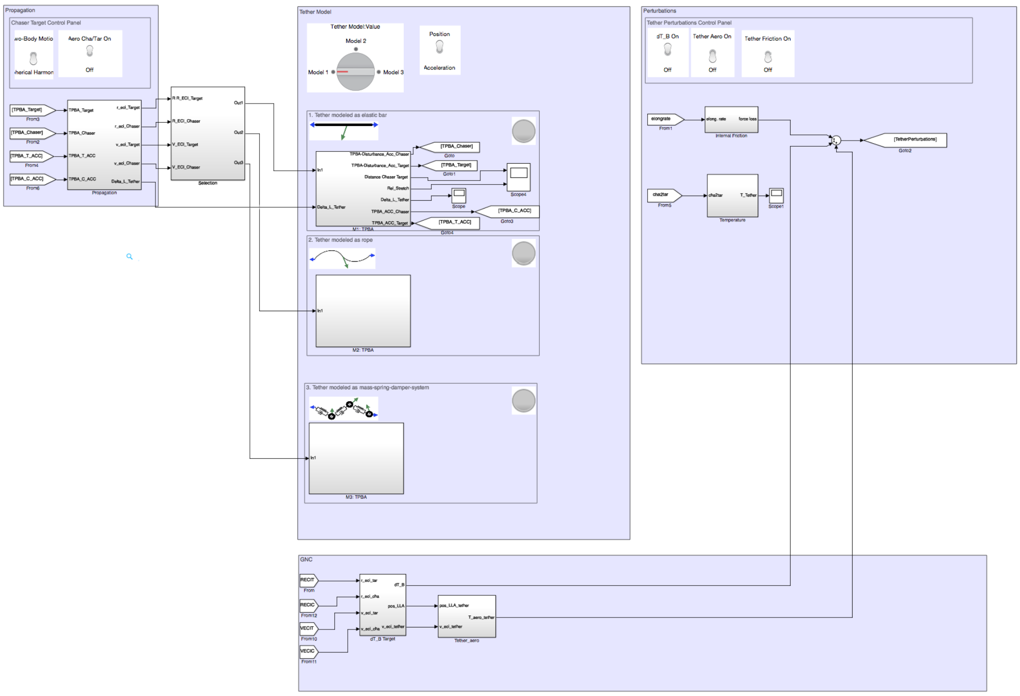

Figure 4. Screenshot Matlab/SIMULINK® Tether Dynamic Toolbox - Simulink® user surface

Figure 4 shows the current user interface of the Matlab/SIMULINK® part of the TDT. On the left is the propagator module followed by the selection box for the tether model. The tether module receives the end-bodies positions and accelerations as boundary conditions for the tether. The GNC module is shown in the lower section, here the connection to the tether module needs to be done to receive an in the loop feedback that can be considered in the simulation process directly.

The next subsections 2.1 till 2.3 provides an overview of the tether simulation models that are intended for the TDT.

2.1. Cat. 1: Bar approach

To describe the tether as a bar is, in relation to the other categories, a simple approach to describe the tether mechanics. However, some results can already be determined and preliminary studies can be carried out. To be taken into account are different approaches depending on the scope of the details of the tether. So, for example, Aslanov describe a model of a mass less connected with two light satellites [11]. In his model, he combines the propagation of the end-masses with the determination of the tether Tension T. Thus he obtains a system of three differential equations of the second order for the description of the force or tension applied to the tether. By selecting a specified orbital plane and setting the tether parameters this system of equations can be solved. Thus the TDT, as described in section 1, is based on a modular approach, the model of Aslanov can not be implemented due to the direct connection of orbital and tether dynamics.

Therefore is in the TDT a specially developed version of a mechanical bar as an approach for tether model included. So the model is focused on the mechanics of a heavy flexible bar. In contrast to the Aslanov model the weight of the bar is considered so it is possible to consider frequency aspects of the tether, e.g. the eigenfrequency which is represented by the square root of the bar constant D and the mass m:

$$\omega_0 = \sqrt{\frac{D}{m}} = \sqrt{\frac{E \cdot A \cdot l_0^{-1}}{m}} \tag{1}$$

with the Young's Modulus E, the cross-section Area A and the initial length l_0.

However, this basic is expanded by some additional functions. One extension is an internal friction model represented by a loss factor δ. While the loss of energy is proportional to the tether tension T and T is a function of the material factor C and the extension Δl:

$$T = D \cdot \Delta l \cdot \delta. \tag{2}$$

For a chaser and target distances less than the initial tether length l_0 also the Tension T is zero. Typical materials for space tethers are Dyneema®, Nylon or Dacron [15]. In an integrated database there are currently 11 different materials from which the user can choose. Other materials can be easily added. In this case, however, it must be taken into account that the absolute values of the tether should be entered, material mixes or inter-material effect are currently not considered. This feature is also not foreseen for the future version because depending on the material mixture several effects (yield strengths and fiber fatigue due to torsion) needs to be considered. For this cases, the user needs to add data from its own material test. The material data can be used for each tether model.

For the next release, it is planned to discretize the heavy bar into at least 100 segments. Irrespective of the tether length it is so possible to analyze various tether geometries regarding its dynamic behaviors. Figure 5 shows some examples of possible tether geometries besides the standard geometry which is shown above. So the second geometry is an even distribution of thickened nodes along the tether to increase the resistance against lengthening and to reduce the absolute amplitude of the oscillations. The third geometry is able to represent attachment points or on side of the chaser also a possible spooling mechanism that might control the length of the tether. Based on the first results, further geometries and approaches are to be determined. On the basis of these simulation results and experiences, a practical consideration can subsequently be made regarding the feasibility of such geometries. In particular, aspects of the storability and requirements for spooling mechanisms must be considered.

This function holds a certain analogy to the third category tether models, where here no direct damping terms are considered. The damping is still represented by the loss factor δ. This still allows for a waiver a solver for a differential equation in the first category. This makes initial assessments and quick solutions possible. A new submodule is inserted for the modeling of the tether or tether parameters so that the other models can also access the changed geometries and no adaptations are necessary when changing the solution approach (model category).

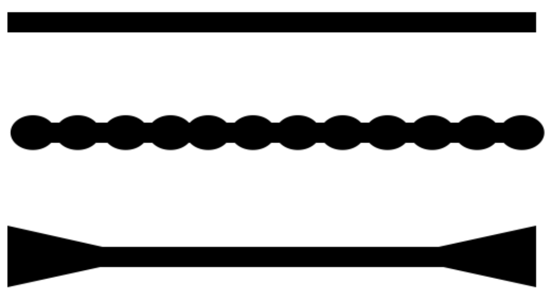

Figure 5. Tether Shapes

2.2. Cat. 2: Continuous thread approach

If the tether is modeled continuously, the tether equation is derived from a force equilibrium at a tether element ds. The tether forces at both ends of the tether $\vec{T}$, the gravitational force, and other interfering forces, which are combined into a vector $\vec{F}$, are applied to this tether element. With the second Newtonian axiom, the equilibrium of forces can be set up as [15]:

$$\rho(s)ds\frac{\partial^2\vec{R}}{\partial t^2} = \vec{T}(s+ds,t) - \vec{T}(s,t) - \rho(s)ds\frac{\mu\vec{R}}{R^3}S + \vec{F}ds \tag{3}$$

Here s is a variable that starts at one of the two end bodies and runs along the t. If the general definition of a derivative is used and divided by ds is [15]:

$$\rho\frac{\partial^2\vec{R}}{\partial t^2} = \frac{\partial\vec{T}}{\partial s} - \rho\frac{\mu\vec{R}}{R^3} + \vec{F} \tag{4}$$

Equation 4 can be further refined by using the tether tension. Due to the definition of the tether as an elastic string, which can only withstand axial stretching, the tether tension force is always tangential. If the tangent vector along the tether is τ, the vector of the tension can be expressed as: [15]:

$$\vec{T} = T\tau, \;\; \tau = \frac{\partial\vec{R}}{\partial s}\left|\frac{\partial\vec{R}}{\partial s}\right|^{-1} \tag{5}$$

Next the size of the tether tension force must be determined. This can be done through various laws of elasticity; Hook's law is chosen here. This computes the stresses σ in the rope from the extensions $\gamma - 1$ and the elasticity module E. The rope force results from the multiplication of the stresses by the cable cross-section S [11]

$$T = \sigma S = ES\left(\gamma - 1\right), \;\; \gamma = \left|\frac{\partial\vec{R}}{\partial s}\right|. \tag{6}$$

If the equations 5 and 6 are used in 4, the following equation 7 is obtained as a partial differential equation reflecting the movement of the tether:

$$\rho\frac{\partial^2\vec{R}}{\partial t^2} = \frac{\partial^2\vec{R}}{\partial s^2}ES\left(1 - \left|\frac{\partial\vec{R}}{\partial s}\right|^{-1}\right) - \rho\frac{\mu\vec{R}}{R^3} + \vec{F} \tag{7}$$

To solve the equation, boundary conditions are necessary. These are the movements of the end-bodies. Since an analytical solution of the equation is not possible, it is solved numerically by means of the finite elements. For this purpose, a Matlab® solver is used which is specifically designed to solve partial differential equations and a Simulink® model that calculates the movement of the final masses and interfering forces.

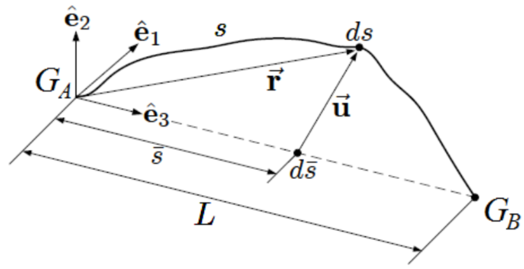

Figure 6. Graphical Model Representation [16]

The Matlab® Solver SOLVEPDE solves equations of form

$$m\frac{\partial^2 u}{\partial t^2} + d\frac{\partial u}{\partial t} - \nabla\cdot(c\nabla u) + au = f \tag{8}$$

Therefore, the equation must be transformed to correspond to this form. The coefficient c must be taken into account as the second derivative has to be transformed by the location into an expression with two ∇ operators. A geometry is then defined on which the equation is to be solved, in this case, a cylinder representing the tether. In addition, the boundary conditions must be entered and the surfaces on which they apply. Therefore, a Dirichlet boundary condition which contains the position of the end mass at the respective end of the tether is defined. After the coefficients m, d, c, a and f have been defined from equation 9, initial conditions $\vec{R}(0,s)$ and $\dot{\vec{R}}(0,s)$ are set . The boundary conditions, as well as the initial conditions and the coefficients, can depend on the location as well as the solution or its derivative. Finally, an finite elements network is defined, consisting of tetrahedra with either four or ten nodes. For the final solution of the equation, a time vector is needed which contains the instants at which the equation is to be solved.

2.3. Cat. 3: Lumped mass approach

This approach subdivides the tether into n spring-damper-mass-systems as shown below in figure 2. Each system can have individual properties (resistance, mass etc.) so also tethers with various geometries can be considered. The dynamics of the system can be described by a system of differential equations.

$$\mathbf{s} = \mathbf{M}\ddot{\mathbf{u}} + \mathbf{B}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} \tag{9}$$

where $\mathbf{M}$ denotes the mass, $\mathbf{B}$ the damping and $\mathbf{K}$ the stiffness matrix of the equations system. In case of an undamped system $\mathbf{B}$ becomes zero.

Preliminary studies showed a massive increase of the computation time for different divided models ($n = 4$ to $n = 20$). Thus, an analysis of the influence of the undercut on the computation time is necessary, taking into account the required precision. For this purpose, the results from the other two models should also be included in order to allow a good estimation of the necessary division of the model into separate spring-damper-mass-systems.

Due to the natural differences in the modeling approaches of each model category the calculation of the TPBA, that represents in all models the connection of the end-bodies with the tether, needs to be adapted. So, for example, the calculation of applying acceleration forces for models in category one and two differs to the tether model of category three. In category three each mass point needs to be considered. Also, differences in damping (energy losses within the tether) needs a different modeling approach. [10]

3. CURRENT STATUS AND ROAD MAP

In this chapter, the current status and an outlook for upcoming tasks are to be given. For this purpose the individual modules are briefly considered:

- **TSpS Propagation**
  The development of the propagation module is currently finished. No additional functions are currently planned. As in [9] demonstrated the most influencing orbital perturbations and effects are covered by the earth harmonics and the aerodynamics; for such short missions as the de-orbiting of a captured spacecraft. The propagation block is two times integrated so is a parallel propagation of chaser and target possible. Other effects that may have an influence are determined in the tether dynamics block and linked to the propagation by the TPBA.
- **Tether Dynamic Modeling**
  This module is currently under development and integration. The first class module is integrated and tested. The second class module is almost integrated, here is just some minor adjustments and test regarding the used solver and solving approach required. It is intended to have a running version until May, to begin with the testing phase. For the third category model, theoretical studies have been done and a simple Simulink module was created. Based on this, the integration will now take place shortly.
- **TSpS Guidance Navigation and Control**
  For this module, some theoretical preliminary work has been done so far. First steps will be the implementation of an algorithm to control the length of the tether to reduce the overall quantity of oscillations and to check if it is possible to an approximate constant tether tension by controlling the length.

Besides the described modules some additional functions are planned to perform several pre-mission or general analysis on this research topic. An example given here is the tether geometry module that allows the prediction and critical analysis of various tether.

After the implementation and integration of the GNC module is a validation of the TDT tool required. For this purpose, some data are already available which still need to be processed accordingly.

4. CONCLUSION

This paper presents the current status and the achieved objectives within the development process of the TDT. Also, a short introduction to the implemented tether models and their integration status is given. In the future the integration of the tether models can be finished and the work on the GNC module can go further. Therefore is the available experimental data very helpful.

However, a lot of evaluations are still needed to be done. The experiment data provides an important input for the general understanding of tethered connection in space and its special use case in ADR missions. In addition, the data and results obtained an important part of the evolution of the theoretically developed and modeled tethers within TDT development progress. First analysis results are planned to present during the ISS R& D conference in July 2017. However, this is more likely to be seen as the beginning. Especially GNC aspects need further analysis that could be done after the GNC module is in the calculation loop included.

Also, the research on the tether geometries needs to be driven forward. Through this, a better tether dynamics performance and stabilization, even during critical mission phases, is expected. Afterward, studies on the feasibility of mechanical apses (storage, spooling etc.) are required. But these needs to be done after a validation of the key aspect of TDT, the dynamic modeling of tethered active debris removal missions to be able to analyze the stabilization and de-orbit phase of the TSpS.

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