Contact Dynamics Simulations for ConeXpress Docking Maneuvers

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INTRODUCTION

Dutch Space is currently developing a general purpose satellite platform called ConeXpress (Fig. 1). As the structure of ConeXpress will also act as payload adapter for the primary or secondary passenger inside the fairing of the Ariane 5 launcher, it can be launched several times per year as a very special kind of auxiliary payload for GEO applications.

One of the potential applications of ConeXpress will be the Orbital Life Extension Vehicle (CX-OLEV) operating as a space tug for telecommunication satellites in the geostationary orbit after their nominal end of life [1]. Hereby, ConeXpress will dock at the client satellite and take over the attitude and orbit control of the overall double-satellite. The CX-OLEV technology was developed within the ARTES 4 public privat partner ship framework of ESA by Dutch Space, Swedish Space Corporation, SENER, Kayser-Threde and their sub-contractors. The according CX-OLEV services are commercially provided by Orbital Recovery Limited [2].

A key operation of CX-OLEV, which is totally different from ordinary satellite missions, is the docking operation at the client satellite (Fig. 2). For this purpose a telescopic boom mounted at the ConeXpress crater floor will be deployed. The boom carries a capture tool on its tip that is dedicated for grasping the apogee kick motor nozzle of the client satellite at its throat. One of the most critical phases during the docking operation is the time beginning with the first physical contact between the capture tool and the inner surface of the client nozzle and ending when the capture tool has established a rigid connection with the client nozzle.

During the CX-OLEV project phase B a large number of docking simulations were performed focusing on the particular problem of physical contact between chaser and client satellite. The goal of the simulations was to estimate the likeliness of successful docking under respect of environmental, mechanical and operational constraints. The applied simulation facility, the relevant contact models and the according simulation results will be presented in the following chapters.
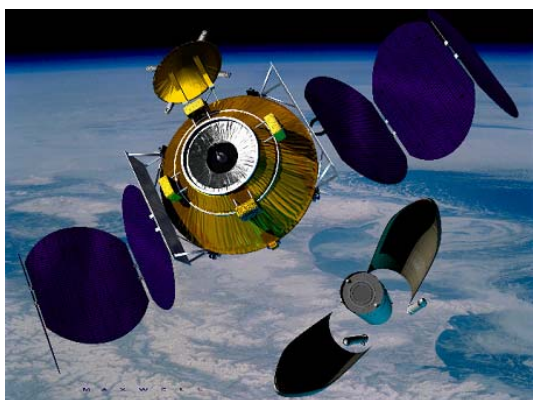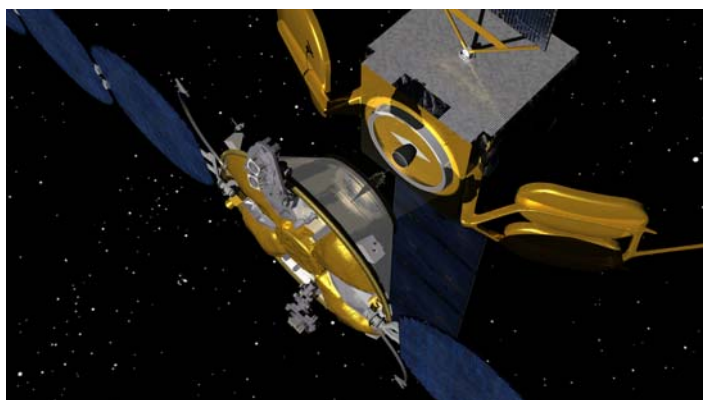

Fig. 1: ConeXpress Spacecraft

Fig. 2: Rendezvous of ConeXpress with Client Satellite

SIMULATION FACILITY – CONEXPRESS SYSTEM FACILITY

To perform feasibility and design analysis for the CX-OLEV program in phase B, the Design Simulator Facility (DSF) was used. The DSF, initiated and maintained by Dutch Space, served as a common platform for all simulations of CX-OLEV performed by the participating parties. The DSF is part of an overall ConeXpress System Facility (CSF, see Fig. 3) concept, which is a collection of facilities that support the design, software verification and validation, hardware testing and last but not least operator training and operation of the ConeXpress mission. In other words it supports the full project life-cycle.

Multiple linked facilities with a common architecture and a project wide system database are some of the key issues:

- *Design Simulator Facility* (DSF): Supports system and control design, operation and mission analysis, development of satellite and environment models and development of onboard software modules, based on MathWorks tools. The DSF was build using a collaborative effort by different companies (see Tab. 1). The environment/dynamics models were based on the Dutch Space GAOCS core with specific extensions for CX-OLEV, e.g. flexible rotating solar panels by Dutch Space and a contact dynamics model by DLR. The spacecraft models were made specific for CX-OLEV, e.g. electrical propulsion and thruster orientation mechanism by Dutch Space, GNC by Sener and GMV, docking payload by DLR and Kayser-Threde.
- *Software Verification Facility* (SVF): Supports onboard software verification and validation i.e. Software-In-the-Loop (SIL) and Processor-In-the-Loop (PIL), system design, development of tests and development of detailed satellite models, including fault injection, based on EuroSim.
- *Electrical Ground Support Equipment* (EGSE): Supports step-by-step integration of spacecraft hardware, execution of hardware validation tests and execution of system and sub-system level tests i.e. Electrical Test Bench (ETB) and Spacecraft Test Bench (STB), based on EuroSim.
- *ConeXpress Reference Facility* (CRF): Supports software maintenance, preparation and testing of flight operation procedures and operator training, based on EuroSim.
- *Operation Control Center* (OCC): Supports mission control and monitoring, specifically for performing the docking operations and data archiving.
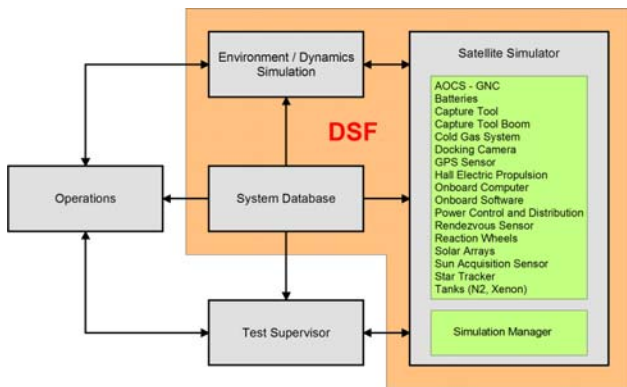

Fig. 3: Architecture of CSF / DSF

Unit	Description	Responsible
BAT	Batteries	Dutch Space
CAP	Capture Tool	DLR / Kayser-Threde
CGS	Cold Gas System	Dutch Space
DCAM	Docking Camera	DLR / Kayser-Threde
DRB	Capture Tool Boom	DLR / Kayser-Threde
ENV/DYN	Environment and Dynamics	Dutch Space / DLR
GPS	Global Position Sensor	GMV
GYR	Gyro	SENER
HALL	HALL Electric Propulsion	Dutch Space
MATH	Mathematical Library	Dutch Space
OBS	AOCS (Guidance Navigation and Control)	SENER / GMV / Dutch Space
PCDU	Power Control and Distribution Unit	Dutch Space
RV	Rendezvous Sensor	GMV
RWS	Reaction Wheel System	SENER
SA	Solar Arrays	Dutch Space
SADM	Solar Array Drive Mechanism	Dutch Space
SAS	Sun Acquisition Sensor	Dutch Space
STR	Star Tracker	SENER
TANKN2	N2 Tank	Dutch Space
TANKXE	Xenon Tank	Dutch Space

Tab. 1: Responsibilities for Simulators Components

In the CSF concept, each facility uses a common architecture that consists of the following main parts:
- *Environment/Dynamics Simulator (ENV/DYN):* Used for simulating sun, moon, earth, orbit, external influences etc.
- *Satellite:* Used for simulating the spacecraft platform and payload. It consists of a simulation manager, a platform simulator (sensors, actuator and support models) and a payload simulator.
- *System Database (SDB):* Used for general project wide accessible database. It contains the Spacecraft Database (on-board database), Flight Dynamics Database and the Operation Database. The underlying approach is the complete separation of data and functions (e.g. algorithms or test procedures). This enables different data views by different type of engineers, an improved configuration control and easier distribution of data to all involved parties. The SDB contains a large number of parameters such as:
  - Environment/dynamics parameters,
  - Spacecraft model parameters,
  - Onboard software parameters,
  - Flight Dynamic parameters,
  - TmTc packet definitions,
  - Test data.
  The inclusion of test data for simulations, system integration and unit tests allows the automatic generation and updates of test procedures. The extraction of the required simulation and test parameters is done automatically.
- *Test Supervisor (TSUP):* Used for overall test session control, monitoring and post-processing of results.
- *Operations*: Used for operations including planning, monitoring and training. It consists of the Mission Control System (MCS), the Mission Planning System (MPS) and TmTc simulator based on SCOS2000.

With help of specific docking simulations a number of crucial questions regarding feasibility of docking and mission success had to be answered:

- Is the approach strategy of ConeXpress suitable in terms of satellite control and operation of the docking payload?
- Is the accuracy of the applied sensors sufficient for the proposed control algorithm and is it possible to extract the desired information from the according sensor data?
- Are the performances of the applied actuators and tools adequate for the dynamics of the system?
- Is there any danger for damaging the client satellite or ConeXpress itself when physical contact between the docking payload and the client satellite takes place?
- etc.

In order to be able to answer these kinds of questions the Design Simulator Facility has been equipped with a high fidelity contact dynamics model by DLR that is able to reproduce the characteristics, the amount and the impact direction of the applied contact forces during the physical contact phases of the docking operation. Since real-time conditions were not required in project phase B of CX-OLEV, a model for variable step size time-integration has been implemented focusing mainly on accuracy in terms of simulation output.

CONTACT DYNAMICS MODEL FOR DSF

The contact dynamics models that have been implemented in DSF are derived from the so-called Polygonal Contact Model (PCM, [3]) and adapted to the particular application inside the simulator. The general idea of PCM is based on three major steps:
1. Discretization of the contact body surface by polygon meshes and assignment of contact relevant geometric and dynamics parameters individually to each polygon.
2. Detection of polygons, which are in contact with their counter part.
3. Calculation of contact forces/torques based on the relative kinematics states of the contact polygons under respect of the assigned geometric and dynamics parameters.

Contact Body Description – Polygonal Contact Surface – Assignment of Physical Properties

The method of creating the polygon meshes takes advantage of the fact that only rotationally symmetric surfaces are involved in contact dynamics events (Fig. 4). Thus, they can be described by their discrete longitudinal section functions (radius versus axial co-ordinate), which may be also a function of further parameters in case of a variable surface shape. The distribution of the sampling points depends on the particular curvature of the longitudinal section function, respectively on the curvature of the body surface: The stronger the curvature, the shorter the distance of the sampling points. These settings guarantee for good sensitivity of the models regarding contact detection at a minimum number of surface polygons. The polygon mesh, respectively its vertices can be created by rotating the longitudinal section around the body axis with discrete angular distances. Within the polygon mesh three adjoining vertices define a so-called face (isosceles triangle).
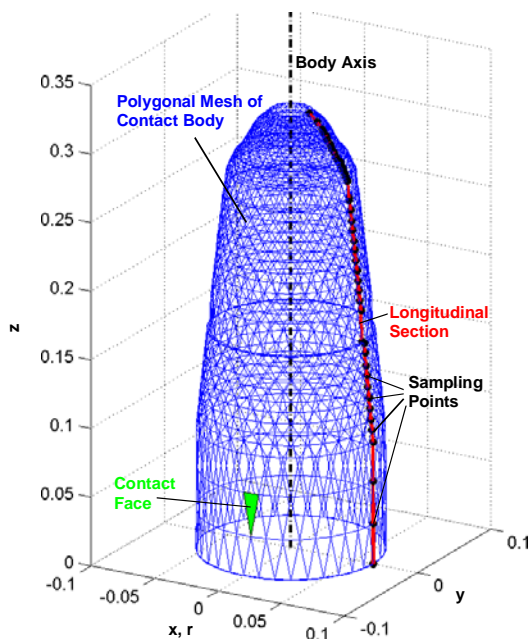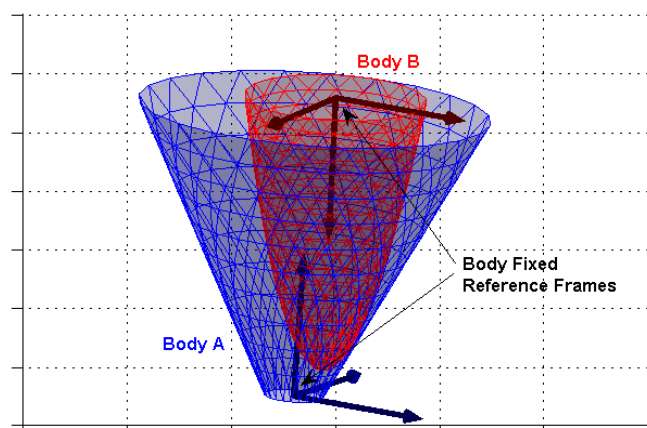

Fig. 4: Contact Body Definition Fig. 5: General Contact Dynamics Scenario

After creating the discrete description of the body surfaces we can assign parameters, which are required for contact dynamics calculations, individually to each polygon face. The first set of parameter consists of geometric properties:

- Face size A,
- Face normal vector $\mathbf{n}$,
- Face center co-ordinates $\mathbf{C}$.

In the second parameter set the dynamic properties will be assigned. Here, each polygon face is interpreted as linear spring-damper system acting in its individual face normal direction. Thus, we assign individual stiffness and damping coefficients c and d. This approach is modeling the surface stiffness as well as energy dissipation during contact.

The physics of Coulomb friction between the surface polygons is represented by individual friction coefficients μ for both, stick and slip states.

Contact Detection – Contact Shape

In order to detect, if a body surface (e.g. Body B, Fig. 5) is intersecting the surface of its reference body (e.g. Body A, Fig. 5), the according polygon vertex co-ordinates of the inspected body have to be transformed into the body fixed reference frame of the reference body as visualized in Fig. 6. In the second step we can map all vertices into a two-dimensional reference frame of radial and axial co-ordinates. Herein the reference body appears as its own longitudinal section (Fig. 7). And following we can compare the radial co-ordinates of the vertices of the inspected body just with the longitudinal section function of the reference body in order to decide about contact or not contact (Fig. 8). From the computation point of view this algorithm is very time-efficient since the number of matrix operation can be reduced drastically compared to contact detection in the three-dimensional space. Moreover, the method can be applied to contact dynamics problems including convex bodies as well as concave bodies and it doesn't cause any limitation in terms of multi-point contact configurations.
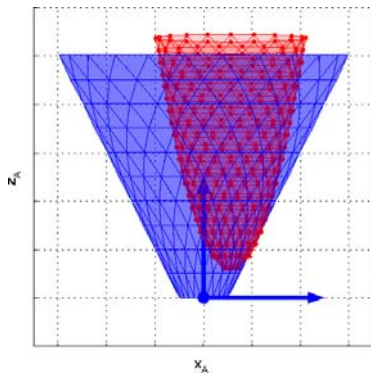

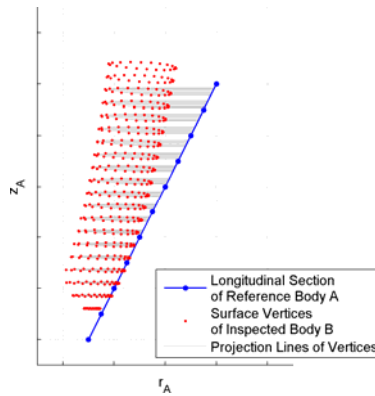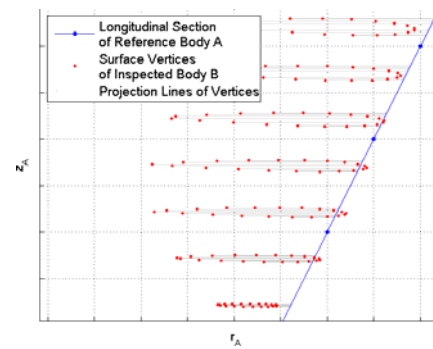| Fig. 6: Body B Transformed Into Reference Frame of Body A | Fig. 7: Body Vertices Mapped From 3D to 2D | Fig. 8: Zoomed View on Vertices in Contact |

After re-mapping of those vertices, which are actually in contact, into the 3D space we are able to define the contact shape by the according polygon mesh grid. Ambiguous solutions at the border of the contact shape (only one or two vertices of the face in contact) will be fixed by a refinement of the regarding polygons and the repetition of the contact detection in an iterative process. This refinement option inside the model is essential since the ambiguous solution is much more likely during running simulations than the unambiguous one (all vertices or none of the vertices of a face in contact).
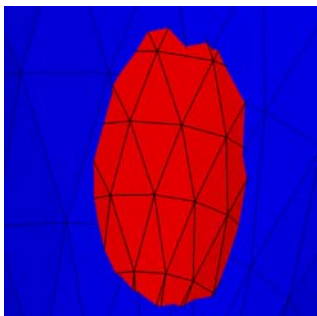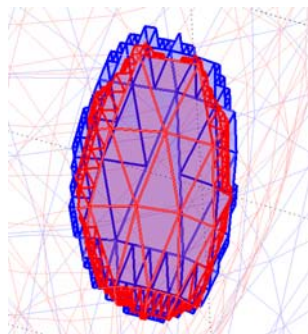

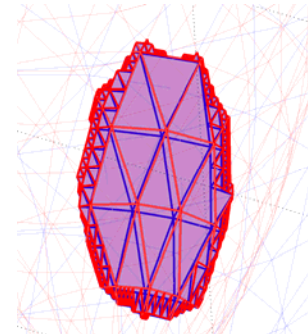| Fig. 9: Contact Shape | Fig. 10: Contact Shape With Boarder Refinement | Fig. 11: Mapped Reference Shape of Contact Shape |

Relative Motion States of Contact Surfaces

Further components for the contact force calculation are the relative motion states of the contact shape polygons, strictly speaking the polygon centers C relative to their counterparts. The required motion states are:
1. Normal penetration depth of the contact polygon into the counterpart polygon s,
2. Normal penetration velocity v_n,
3. Relative tangential velocity between the contact polygon center w.r.t the surface of the counterpart v_t.

Hereby, the counterpart polygons can be found by mapping (radial projection) the contact shape polygons onto the surface of the reference body. The relative motion states between two counteracting polygons can be easily found, first by calculation of their absolute motion states based on the absolute motion states of the contact bodies they belong to (model input parameter) and secondly by subtraction of the absolute values.

Contact Forces

With the pre-requisites, which were introduced in the previous chapters, namely
- the dynamics parameters of the polygons and
- the current relative kinematics states,

we are able to calculate the actual contact forces, individually for each contact polygon by the sum of the following components (for simplification reasons only as scalar description):
1. Normal force due to surface stiffness: $F_c = c \cdot s$.
2. Normal force due to damping: $F_d = d \cdot v_n$.
3. Tangential force due to Coulomb friction: $F_\mu = \mu (F_c + F_d)$

The total contact force applied to the contact bodies will be calculated by integration over all polygons of the contact shape.

In the implementation for the ConeXpress simulator the presented contact model (contact detection and contact force calculation) was done two times while in the second one the roles of inspected body and reference body where permuted. This procedure guarantees for the correct contact detection independent from the relative position of the contact bodies. However, caused by the differences in the discrete contact surface resolution as documented in Fig. 7 the actual contact forces would slightly differ from each other. In order to be compliant with Newton's third law of motion (actio = reactio) we apply the mean value of both computations as the final contact forces.

DOCKING SIMULATIONS

This chapter focuses on the simulation results of the most critical phase of the docking operation that takes about two minutes. In this phase the Capture Tool (see also 'Introduction')
1) gets in physical contact with the client nozzle,
2) passes the nozzle throat,
3) opens its Locking Crown,
4) locks the client nozzle and
5) starts to retract the client satellite.

The simulations were performed as pure dynamics simulations in the three-dimensional space without any kinematics constraints or simplifications. Therefore, it is assumed that the reliability of the simulation results is sufficient for an assessment in terms of satellite docking success.

Docking Simulation Scenario

The simulation scenario supposes a R-bar docking procedure in GEO (Fig. 12 and Fig. 13). The initial position of ConeXpress is the so-called parking position with ConeXpress limit cycling at a distance of 30 cm away from the nozzle rim. The initial misalignment between the Capture Tool axis and the nozzle axis is supposed to be 3 cm with equal components in V-bar and H-bar direction. The satellites are controlled by their AOCSs. Moreover, the client attitude is stabilized by a one-axis gyro. The deployment of the Capture Tool is realized by a flexible telescopic boom with a deployment velocity range of +/- 4 mm/s.

The success of docking depends strongly on the control algorithm of the Capture Tool deployment, respectively the boom deployment. The underlying strategy is such, that the deployment velocity will be significantly reduced if physical contact between the Capture Tool or its Locking Crown and the nozzle is expected. Then, the contact energy can be minimized. And following, the boom drive is able to superpose the passive lateral motion caused by bouncing after contact with an active deployment motion such, that the trajectory of the Capture Tool tip travels without contact along the nozzle contour towards the nozzle throat. The position of the Capture Tool tip can be derived from the radial measurements of the laser distance sensors mounted on the Capture Tool together with the knowledge about the nozzle

shape. For passing the nozzle throat the deployment speed will be increased to its maximum. Four limit switches indicate the maximum penetration of the Capture Tool and activate the Locking Crown. This device will be spread quickly and retracted into the Capture Tool. Hereby, the nozzle will be locked and safely attached to the Capture Tool. Now the critical phase of the docking is finished and the boom can be retracted in order to pull the client satellite against a dedicated support mechanism at ConeXpress. For safety reasons the docking strategy offers the option to activate axial thrust forces at ConeXpress. These are required to accelerate ConeXpress if the measured approach velocity differs too much from the boom deployment velocity.
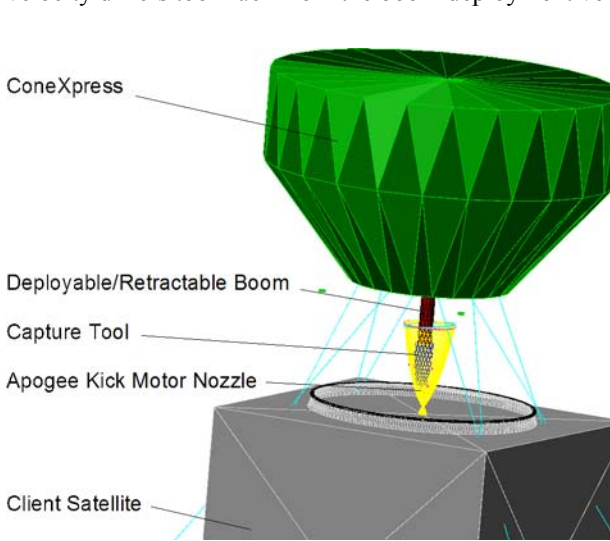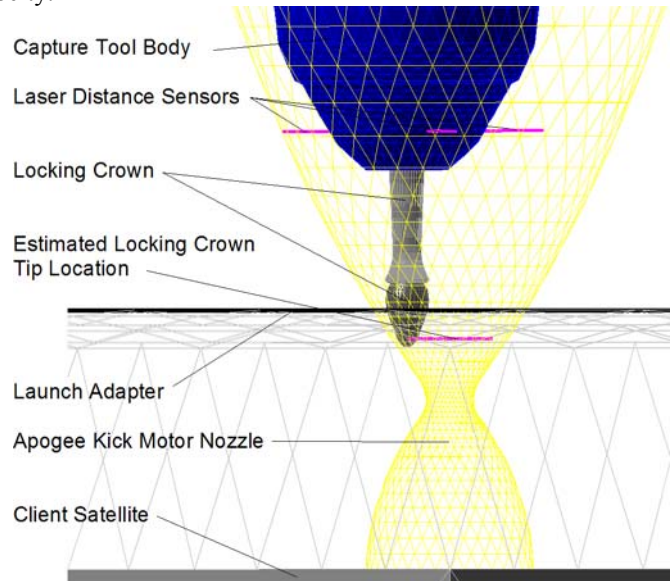

Fig. 12: Scenario of Docking Simulation

Fig. 13: Zoom View on Client Nozzle

Docking Simulation Results

The docking simulation results according to the scenario mentioned above are presented in Fig. 16 with a protocol like discussion of the according function plots in Tab. 2. The legend in Fig. 17 explains the meaning of the presented function plots. The presented results are representative for a large number of similar simulations, which were performed in CX-OLEV phase B in order to prove the robustness of the proposed docking strategy. Concluding we can state that in all simulations the docking could be finished successfully. It was proven, that the accuracy of the proposed sensors at the Capture Tool as well as the performance of the proposed boom and Locking Crown actuators Fig. 14 have been designed adequately.
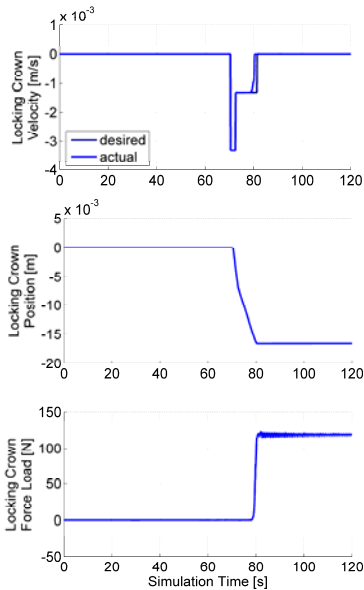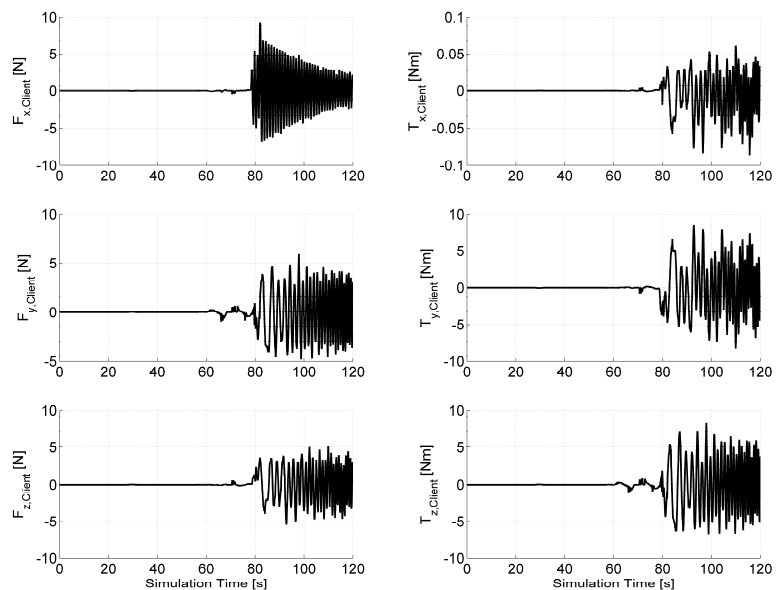

Fig. 14: Locking Crown Operation

Fig. 15: Force/Torque Impact on Client Satellite

Beside the kinematics aspect of the docking it is has to be proven that client satellite will not be damaged during the docking maneuver. According to the presented simulation results the force/torque impact at the client satellite (reference point = center of mass) is quite moderate (Fig. 15). The actual amount of forces and torques is always lower than 10 N, respectively 10 Nm, which is definitely less than the applicable force/torque limits.
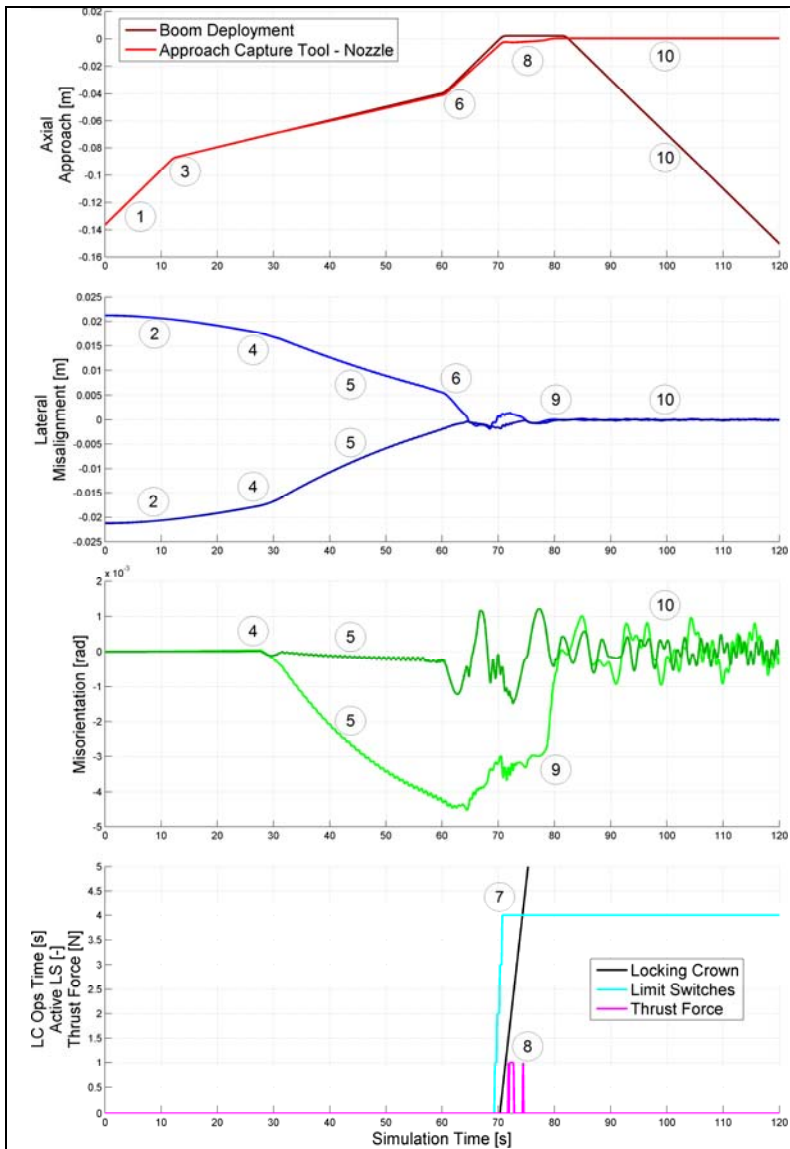
Fig. 16: Capture Tool Approach during Docking
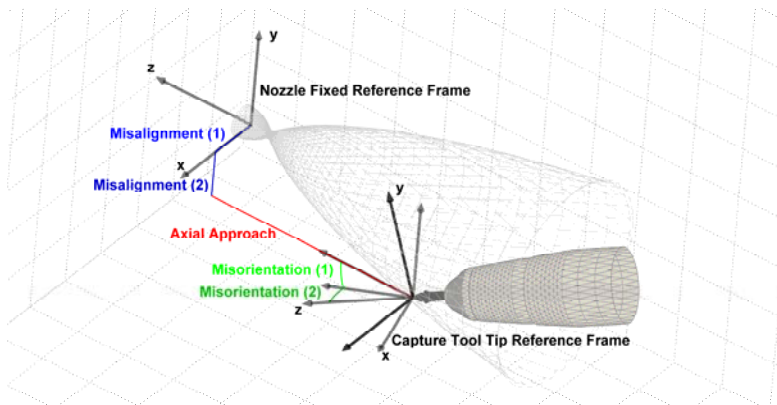

Fig. 17: Legend for Capture Tool Approach

(1) The Capture Tool is being deployed with maximum velocity of 4 mm/s. No physical contact between the Capture Tool and the nozzle is expected.

(2) The AOCS of ConeXpress reduces slightly the initial lateral misalignment.

(3) The Capture Tool, respectively its Locking Crown is now close to the nozzle surface. The deployment velocity will be reduced to 1 mm/s in order to minimize the expected contact shock energy.

(4) Physical contact between the Capture Tool and the nozzle takes place.

(5) The Capture Tool tip bounces and moves laterally towards the nozzle center line. Caused by the torque of the contact shock the satellites start to turn. However, the gyro at the client can minimize the amount of misorientation in one of the affected satellite axes.

(6) The Capture Tool tip has reached the nozzle throat. For passing the throat the deployment velocity will be increased to 4 mm/s.

(7) After passing the nozzle throat, four limit switches at the Capture Tool shoulder indicate that the Locking Crown has to be activated.

(8) Since the measured approach velocity differs too much from the boom deployment velocity, the axial thrusters of ConeXpress fire with 1 N in order to correct this error.

(9) The Locking Crown locks the client nozzle. Lateral misalignment and angular misorientation disappear.

(10) The locking force of the Locking Crown is about 100 N (see Fig. 14). This amount is sufficient to keep the connection between Capture Tool and nozzle stiff enough during the boom retraction phase.

Tab. 2: Docking Protocol

OUTLOOK

With help of the presented simulation results it was proven, that the proposed docking strategy for CX-OLEV works properly and reliable. However, the accuracy of the simulation depends strongly on the fidelity of the models and the knowledge about the according system parameters. And it is obvious that in the current CX-OLEV project phase only a limited number of parameters is exactly known. This applies especially to the simulation of mechanical and physical phenomena. Therefore, the models still include simplification that should be eliminated in the following project phases.

In the frame of CSF, the simulator improvement follows a step-by-step approach by implementing more and more flight components. The step-by-step approach that results in a ConeXpress Reference Facility suitable for operations test and training as well as for parallel simulations after mission launch is visualized in Fig. 18. The according components are already explained in chapter 'Simulation Facility – ConeXpress System Facility'. Together with the implementation of flight hardware and human operators into the simulation loop the real-time capability of the simulator becomes mandatory. In case of CSF this capability will be provided by an automated migration (Fig. 19) of DSF models from the Matlab/Simulink platform to the EuroSim platform, which provides hard real-time scheduling for the simulation process.
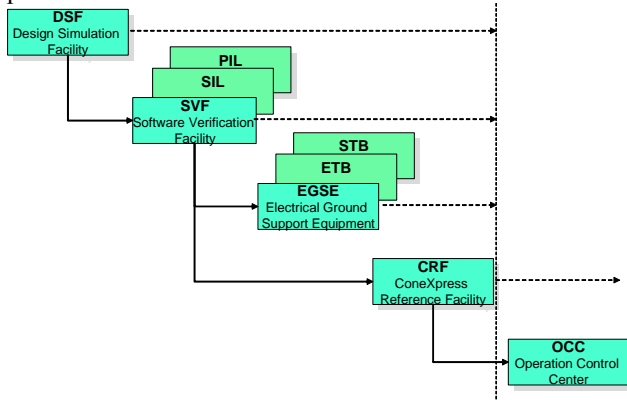

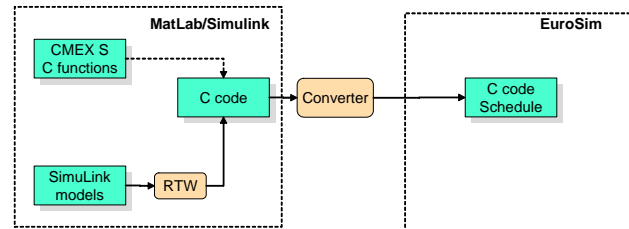Fig. 18: Step-by-Step Approach of CSF Development

Fig. 19: DSF Model Conversion to EuroSim

From the contact dynamics point of view the CSF step-by-step approach can not be realized as proposed above since the computation time needed for a correct calculation of the contact dynamics exceeds significantly the available time slot in the real-time schedule. The preferable solution is the so-called Hybrid Simulation method. Hereby, non-flight hardware will be included into the simulation loop. In case of ConeXpress docking simulations robotic devices will be utilized in order to perform physically the calculated trajectories of the contact bodies (Fig. 20 and Fig. 21). Then, the bodies will have also physical contact during the docking simulations and the measured contact forces can be fed back into the real-time simulator, where the trajectories of the contact bodies will be updated accordingly. In this loop the contact model will be replaced by a real, time-continuous contact event. Nevertheless, contact dynamics simulation remains still a challenging task [4], since now the appropriate control of the robot trajectories moves into the focus of the simulator development.

Fig. 20: Hybrid Simulation with Robotic Devices (DLR, Inst. of Robotics and Mechatronics)

Fig. 21: European Proximity Operations Simulator – EPOS (DLR, German Space Operations Center) Utilized for Long-Range Docking Maneuvers Within CX-OLEV

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