USING ROBOTS FOR ADVANCED RENDEZVOUS AND DOCKING SIMULATION

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ABSTRACT

For human spaceflight missions rendezvous and docking (RvD) of two spacecrafts is state of the art today. For future satellite missions this close operation scenario has become more and more interesting during the last years. These comprise so called on-orbit servicing missions (OLEV, DEOS) as well as exploration missions (Mars Sample Return). One of the critical issues of such missions is to ensure a safe and reliable rendezvous and docking process. Since the RvD process is known to be the most risky part, these operations must be carefully analyzed, simulated and verified before the mission can be launched.

Required by the new type of satellite missions DLR set up a completely new and more advanced RvD simulation facility in 2010. The new facility called EPOS 2.0 has full test and verification capabilities for on-orbit servicing missions as well as other RvD scenarios. The facility is based on two large industrial robots to deliver the 6-DOF motion in a representative maneuvering space for typical rendezvous and docking operations. The test bed allows simulation of the last critical phase (ranging from 25m to 0m) of the final approach process including the contact dynamic simulation of the docking process.

For the last two years the facility has been continuously extended for different RvD applications which are described hereafter.

INTRODUCTION

Rendezvous and docking/berthing (RvD/B) operations are key technologies in multi-spacecraft missions, for example in On-Orbit Servicing missions. The rendezvous process consists of several controlled orbital maneuvers in which an active spacecraft (called chaser) approaches a passive spacecraft (called target) in its orbit. In the consecutive mating phase (docking or berthing) the target is captured and the two spacecrafts are structurally connected. A critical step for such missions is the successful rendezvous and docking to the target satellite in orbit. Therefore, this RvD/B process has to be thoroughly tested and verified before a real space mission can be launched.

The typical ground-based simulation, testing and verification process consists of three parts:
- functional numerical simulations,
- processor in the loop (PIL) simulations where the onboard computer is involved in the processing loop and
- hardware in the loop (HIL) simulations where real flight hardware such as sensors or actuators are involved in the simulation.

While the first two simulations can easily be realized, the HIL simulations are difficult to realize because the sensors have to be stimulated like in space. Robot systems are typically used for stimulating rendezvous sensors, as demonstrated in [1], [2], [3] and [4]. Here the greatest challenges are the position accuracy of the robot system and the realization of utmost realistic illumination conditions. For the docking simulation there exist different options, for example air floating tables or parabolic flights, but these options deliver very limited results. Only a robotics-based active gravity compensation system has no limits on the complexity of the space docking system to be simulated or tested while still retaining a full 6-DOF motion condition. Plus, it can use real physical contact hardware to generate contact forces and thus it is more accurate than any mathematical contact dynamics model used in computer-based simulation. This scenario is demonstrated in [3], [5], [6] and [7].

DLR has more than two decades of experience in the field of simulating RvD processes using robot systems. The EPOS facility located at DLR Oberpfaffenhofen was a test bed jointly developed by ESA and DLR for the simulation of spacecraft maneuvers notably over the last few critical meters of the rendezvous phase. The last intensive utilization of the facility was the test and verification of the ATV RvD sensors and systems which are used for the approach to ISS. It was also used for testing RvD sensors of the Japanese HTV.

The upcoming new applications for satellite on-orbit servicing missions require a facility to be able to provide the following test and simulation capabilities:

a) the 6-DOF relative dynamic motion of two satellites in the final approaching phase from 25 meters to 0 meters,
b) the 6-DOF contact dynamic behavior during the entire docking process including the initial impact, soft docking, and hard docking (final rigidization),
c) the space-representative lighting and background conditions.

The old facility was technologically outdated and could not fulfill the new requirements. Therefore DLR decided to set up a new robotic system called EPOS 2.0.

A detailed overview of the current status of EPOS is given in the following chapter including all upgrades of the last two years. The paper continues with the implementation of a closed loop rendezvous scenario based on a camera sensor which is the first rendezvous application using EPOS 2.0 facility. Furthermore the paper presents the docking simulation concept and the first results for docking simulation.

EPOS 2.0

Architectural Design

Since the former EPOS facility apparently could not provide all of the required capabilities, it was replaced completely by a new EPOS system. The design and construction work of the new facility began in 2008. The development work was a joint effort of two institutions of DLR at Oberpfaffenhofen. The first institution is the German Space Operations Center (GSOC), where the facility is build up and it was responsible for the overall design and construction of the facility. The second contributing institution is the DLR's Robotics and Mechatronics Institute, which provided expertise in space robotics technology and some HIL simulation experience.

The facility comprises a hardware-in-the-loop simulator based on two industrial robots (of which one is mounted on a 25m rail system) for physical real-time simulations of rendezvous and docking maneuvers. This test bed allows simulation of the last critical phase (separation ranging from 25m to 0m) of the approach process including the contact dynamics simulation of the docking process.

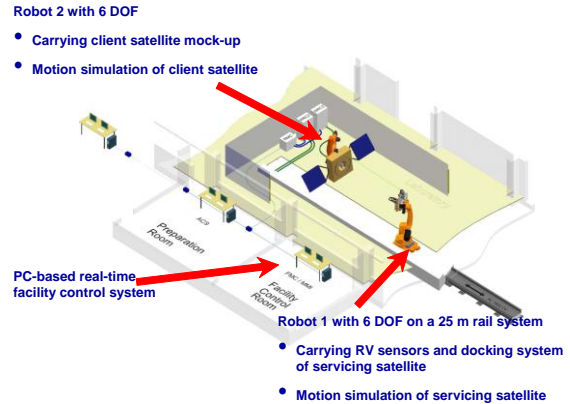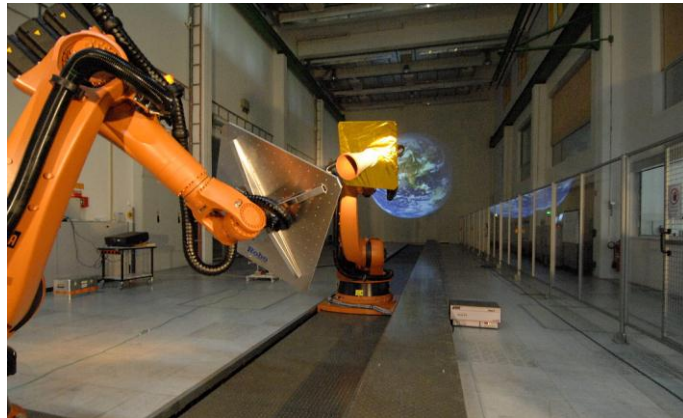The new facility consists of the following components [8]:

Fig.2   The new EPOS facility: robotics-based testbed (left) and a hardware overview (right)

- rail system mounted on the floor to move an industrial robot up to a distance of 25m,
- KUKA KR100HA robot (robot 1) mounted on the rail system for simulating the 6 degree of freedom of one spacecraft,
- KUKA KR240 robot (robot 2) mounted at the end of the rail system for simulating the 6 degree of freedom of the second spacecraft,
- PC-based monitoring and control system to monitor and control the RvD simulation.

Control Concept
The entire control system can be divided into three levels (see Fig. 3):
- the Local Robot Control (LRC) system,
- the Facility Monitoring and Control (FMC) system,
- the Application Control System (ACS).

Regarding the HW items, each robot is independently controlled in real-time by its own LRC unit, provided by the robot manufacturer.
At the FMC level the entire facility is controlled and monitored in real-time. Moreover, the FMC system allows the following tasks:
- operator's monitoring action over all the parameters and states of the facility,
- logging of all the parameters and states of the facility, including external synchronization signals,
- real-time control of the entire facility including synchronization of all motion devices and kinematical conversions of the external commands,
- choice among different interfaces (IF). The following options are available:
    o a synchronous IF (EtherCAT), for closed-loop applications,
    o an asynchronous IF, in order to run a predefined trajectory stored in a file,
    o a KUKA Robot Sensor IF (RSI) to directly interface the FMC with the LRC units.

Finally, at the ACS level, the actual application of the dynamic system is run. In particular, the models of the satellites dynamics and the case-specific scenarios can be implemented in a MATLAB/Simulink environment. This means that the whole software related part of the simulation can exploit a model-based design approach. According to it, MATLAB/Real-Time Workshop can be used to accomplish the automatic code generation. Subsequently the real-time executable is downloaded to a target platform running under the VxWorks operating system. The desired motion commands must be sent every 4ms to the facility, as requested by the LRC units.
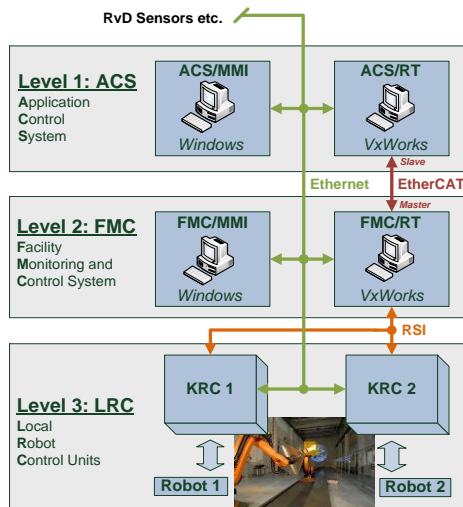
Fig.3   EPOS control concept

Tab. 1 EPOS motion capabilities [9]

Parameter	Robot 1	Robot 2
Position:		
X	-2,5 - +24,5m	-2,5 - +2,5m
Y	-2,5 - +2,5m	-1,0 - +4,0m
Z	-0,5 - +1,5m	-0,5 - +1,2m
Roll	-300 - +300deg	
Pitch	-90 - +90deg	
Yaw	-90 - +90deg	
Velocity (Trans., Rot.):	2m/s , 180deg/s	
Acceleration (Trans./Rot.):	2.3m/s² , 100deg/s²	
Position accuracy [3D/3 σ] (Trans./Rot.):	<2mm / <0.2deg	
Payload:	60kg	200kg
Command rate:	250Hz	

Capabilities and Performances

The EPOS motion capabilities and performances are summarized in Tab. 1. Further details about the facility, the interfaces and its performance are summarized in [9].

Interfacing to advanced external Spacecraft Simulators

In opposite to the above presented scenario where the entire GNC and dynamic simulator s/w are implemented in EPOS-ACS the following other scenario can be considered: A customer has developed its own spacecraft dynamics simulator specifically designed to support the development of a rendezvous camera system. This simulator shall be used to perform real-time HIL rendezvous simulations on EPOS. The integration of such external simulators induces various problematic tasks:

- the customer simulations code has to be ported on EPOS-ACS. Possible incompatibilities with the used real-time operating system VxWorks may require major changes to the code.
- the external simulation system could include other hardware which is connected to it, e.g. an on-board computer. These interfaces have to be provided by the EPOS-ACS which could be difficult to implement.
- The simulation on the ACS/RT has to run at a sample frequency of 250Hz. However, satellite flight software (and associated simulators) may run at considerably lower frequencies.

One solution to avoid these problems is to define an interface where the external simulator can be connected to EPOS. Due to the low bandwidth requirements (position commands with max. 10Hz) a simple Ethernet connection seems to be sufficient. No development work is required, except the implementation of the communication protocol. Ethernet is an established standard so that almost any conceivable simulation system is equipped appropriately. Moreover, the external simulator doesn't necessarily have to be located in the EPOS control room.

This communication interface has been implemented in C++. The code is integrated into Simulink as c-mex S-function blocks. Thus, one S-function block (denoted "server") is part of the Simulink model on EPOS-ACS. Another S-function block is part of the Simulink model running on the external simulator. The blocks establish the Ethernet connection between both Simulink models using a TCP-IP protocol. In general, the external simulator calculates spacecraft states (position, speed, attitude, angular velocity) as part of the individual simulation. These states are fed to the S-function block which sends them to the EPOS S-function block. There, the states are used to have the robots move accordingly.
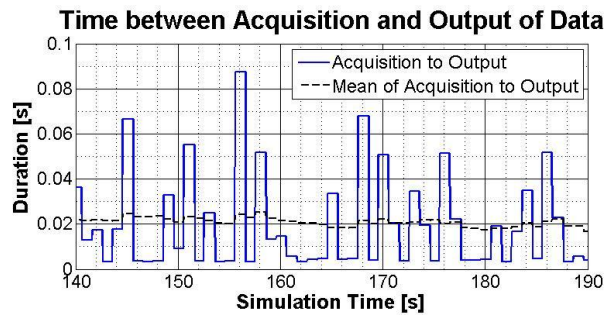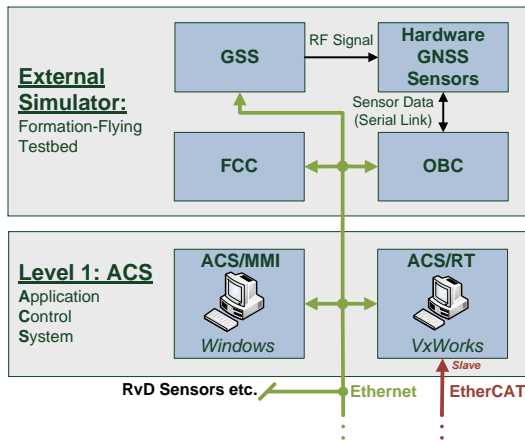
Fig. 4   Concept of Ethernet-IF to an external simulator (left) and its performance (right) [10]

As first test this scenario was implemented using DLR's Formation Flying Testbed [11]. It is an advanced spacecraft dynamic simulator which was developed to realize high-precision HIL-simulations of GPS-based formation flying missions (PRISMA, TanDEM-X). This scenario is depicted in Fig. 4.

One important question is: how does this non-deterministic interface work under real-time simulation conditions? Several tests have been made to analyze the occurring delays and jitter. It can be stated that the mean delay between the command is generated at the external simulator (Acquisition) and the time where this command is available for further processing an EPOS-ACS side is no longer than 20ms (maximum measured value <100ms). This delay times are distinctly below critical values for the command interface which shall run with 10Hz.

Illumination Simulation

An important role plays the generation of realistic sun lighting conditions (like in space), especially concerning the reproduction of light with the Sun's irradiation intensity and spectrum.

As a requirement for sun-simulation it was aimed to achieve the same irradiance of approximately 1.35kW/m² like the Sun has at an Earth orbit. The illuminated target size shall be more than 3m x 3m. In addition to that a sun-like spectral power distribution should be present in the visible region of the light-spectrum.
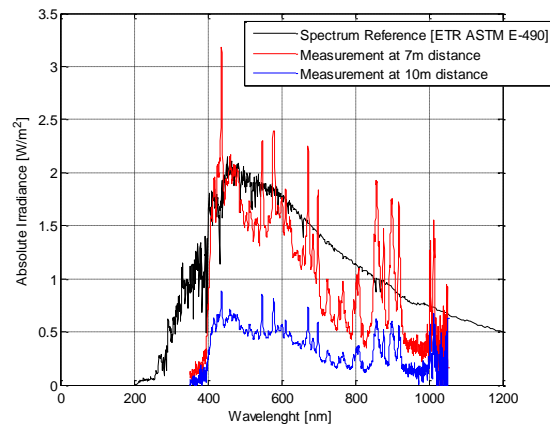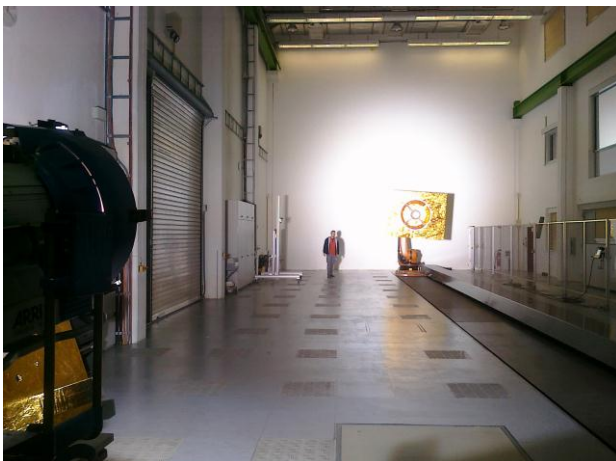

Fig. 5   EPOS illumination system (left) and its performance (right)

To achieve these requirements a suited studio floodlight was selected which is a compromise between the high performance requirements for sun simulation and the technological and economic feasibility. The most powerful studio floodlight currently available is the ARRIMax12 using halogen-metal vapour discharge lamp. This lamp is capable to generate a luminous flux of $1.15*10^6$ lumens with 12kW luminant. This halogen-metal vapour discharge lamp can generate utmost realistic sun's irradiation spectrum.

Fig. 5 shows the measured irradiance of the new Sun simulator at different distances. As reference the ASTM E-490 standard of the solar irradiation at Earth outside the Earth atmosphere is given (black line). At 7m distance to the flood light the best performance can be achieved between 400 to 700nm. Below 400nm the lamp couldn't produce a significant irradiance and above 700nm (excluding 900+/-50nm) the irradiance decreases by factor two.

CLOSED LOOP RENDEZVOUS SIMULATION

One of the goals of performing a hardware-in-the-loop (HIL) simulation at EPOS 2.0 is to simulate an approach to a target satellite for verification and validation of the rendezvous GNC system. For a first setup the following concept of rendezvous HIL-simulation is used:

As navigation sensor a monocular camera is used to measure the relative pose of a mock-up of a Geo-stationary target satellite. The sensor is mounted on one manipulator while the other robot is carrying a target mockup. So the sensor is stimulated by the movement of both robots. A new developed image processing algorithm tracks the outer edges of the satellite body under different illumination conditions. The output of the image processing (the relative state of the target satellite) is fed in a navigation filter which realizes a smoothing of the noisy camera measurements based on the S/C dynamics. A classical PID controller controls the motion states of the approaching satellite w.r.t. the guided trajectory and the current navigation measurements. Based on the computed thruster commands the S/C dynamics and kinematics are numerically calculated which deliver the motion commands for the robots. In the next sample, the computed poses are commanded to the facility. The satellite states, the relative position and attitude trajectory are realized by the robot manipulators. These manipulators can be regarded as the connection of the numerical HIL-simulator with the embedded system.

The complex software functionality for relative guidance, navigation and control (GNC) and for the satellite dynamics is developed under Matlab/Simulink environment and auto-coded with Real Time Workshop. Interfaces to additional hardware components (e.g. the camera as rendezvous sensor) have been established.
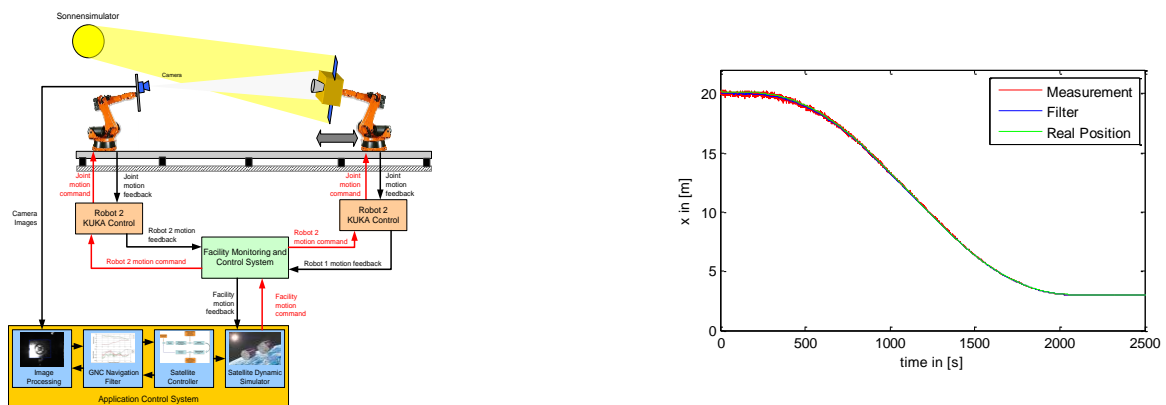

Fig. 6   Rendezvous HIL concept (left) and result of approach simulation (right) [12]

Additionally, Matlab/Simulink supports a multi-tasking execution of a model. The satellites' dynamics runs with a frequency of 250Hz which is the commanding frequency the facility requires. Therefore position and attitude commands are sent to the facility every 4ms. Components with higher computational effort are executed with a lower frequency. So the image processing runs with 5Hz and the GNC part of the s/w-model runs with 10Hz which is a typical number for space applications.
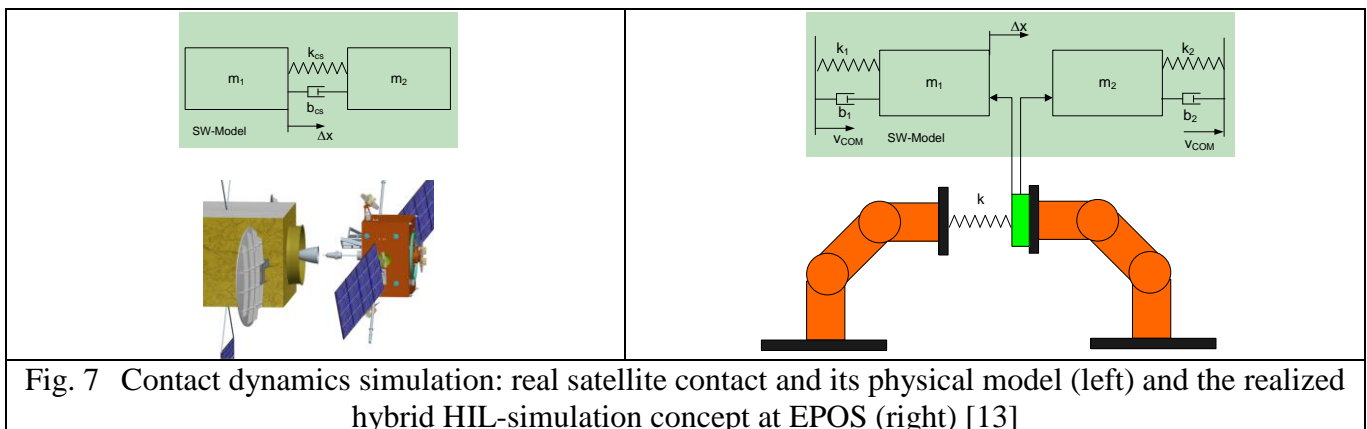
Fig. 6 shows this hardware in the loop simulation concept. Furthermore on the right side the result of an approach simulation from 20m to 3m is provided. It shows that the implemented closed loop on EPOS delivers a stable simulation. The overall performance accuracy has a 3D value of better than 100mm.

This concept can be used for future HIL rendezvous simulations. It allows easily changing components, i.e. replacing the sensor with another one or integrating an onboard computer instead of the implemented s/w GNC-models.

DOCKING SIMULATION

The second goal of performing a hardware-in-the-loop (HIL) simulation at EPOS 2.0 is to simulate on-orbit docking for verification and validation of the docking phase. However, this closed-loop docking simulation is influenced by the response time delay of the entire control loop and by the high stiffness of the robots. The high stiffness causes an unrealistic high impact force which puts the safety of the facility at risk and also results in high contact frequencies compared to the bandwidth of the EPOS 2.0 controller. In addition, the controller time delay destabilizes the HIL simulation when the contact force is fed back to satellite simulator by adding energy to the system.

In order to analyze the effect of the controller time delay and to reproduce the impact characteristics of the satellites a new contact dynamics model is introduced which is based on combining a mechanical compliance with a virtual compliance (see Fig. 7 right). The motivation of this work is to obtain any predefined stiffness and damping characteristics (within some given range), which would generally require a physical replacement of the mechanical compliance for different test scenarios. The method allows changing the total compliance using software and therefore being able to use the same mechanical compliance at the end-effector. The passive mechanical compliance is introduced between the end-effector of one robot and the docking interface probe mounted on the other robot. This is combined with an active position based impedance controller for both robots, described by k_1, b_1, k_2, b_2 in the Fig.7 (right), which can be tuned off-line to arrive at any predefined spring-dashpot contact model behavior or any other desired values. The desired predefined behavior can be dictated by a mathematical impact model for the two satellites, with known impact characteristics. The effect of the passive compliance is to lengthen the duration of the impact, thus avoiding the undesired consequences of the aforementioned time delay.

Fig. 7   Contact dynamics simulation: real satellite contact and its physical model (left) and the realized hybrid HIL-simulation concept at EPOS (right) [13]

SUMMARY

This paper has reported the current status of the new rendezvous and docking facility EPOS 2.0. A detailed overview of EPOS is given including all upgrades made in the last two years. Moreover the paper presents the implementation of a closed loop rendezvous scenario based on a camera sensor which is the first rendezvous application using EPOS 2.0 facility. Furthermore the paper provides the docking simulation concept and the first results for docking simulation.

It has been shown that the facility is ready for HIL rendezvous and docking simulations and the overall simulation structure has been established. Forthcoming development will use this existing simulation structure and can focus on detailed component developments.

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