Next-Generation Opto-mechatronic systems

Next-Generation Opto-mechatronic systems: control for free-space optical communication

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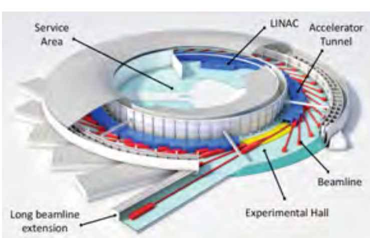
I. Research Overview

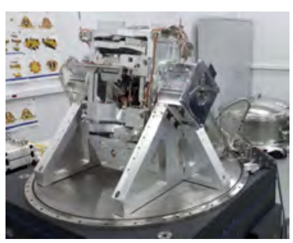
Opto-mechatronics is a multidisciplinary field of expertise in which physics and engineering come together to create novel instruments and systems. Nowadays, opto-mechatronic instruments can be found in many semiconductor, astronomy or space applications, and it is gaining popularity both in research and industry; both in high- and low-tech domains.

In our research we focus on two different trends that we recognize in recent developments in opto-mechatronics. As discussed next, these trends are partly motivated by the domain in which opto-mechatronics is employed.

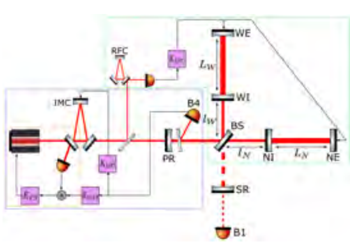
Novel complex concepts and systems

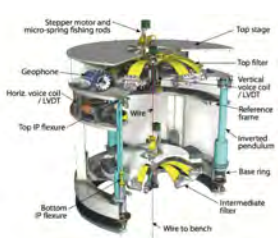
In many *scientific* applications there is a trend towards novel and more complex opto-mechatronics concepts, with larger complexity in e.g. the optical and mechanical designs.



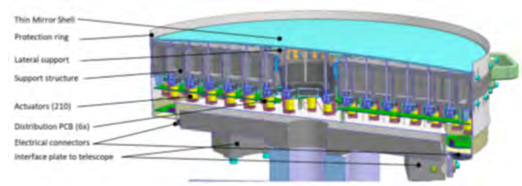


One example is our work on systematic design philosophies for a High-Dynamic Double-Crystal Monochromator for the Sirius synchrotron [1], in which, among others, dynamic error budgeting techniques have been employed to design and create an opto-mechatronic machine concept with unsurpassed accuracy and scanning possibilities.





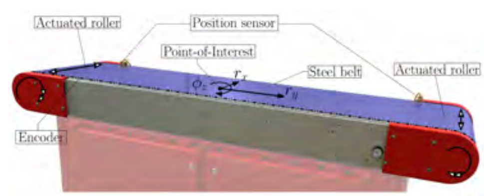
Controller design for such systems is not straightforward, e.g. due to their multi-variability and non-linearities. In our work for the Virgo gravitational wave detector [2] we offer systematic controller design procedures, which have delivered improved performance on the sensitivity of the detector.



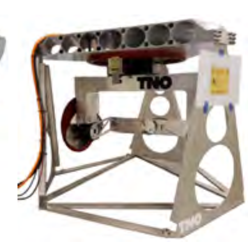
Multi-variability comes to an extreme in Adaptive Optics (AO), which utilizes deformable mirrors (DMs) with hundreds of actuators. Our work on DMs [3] focuses on the dynamic identification and systematic control synthesis of such massive-MIMO systems.

Maintaining performance with lower costs

In *industrial* applications we see a cost-reduction trend, in which opto-mechatronic products need to be built with cheaper, less-performing components, while system performance needs to be maintained.



Our work on a substrate carrier led to novel Gaussian Process (GP) repetitive control approaches [4] to compensate for imbalances introduced by non-perfect mechanics.



This technique has also been employed to improve commutation of Coarse Pointing Assemblies (CPA), while GPs have also been successfully applied in calibration of test benches [5] meant for mass production of such CPAs.

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[5] Also with the Delft Center for Systems and Control, Delft University of Technology, the Netherlands.

II. Seminar Topic - *Free-space optical communication*

In free-space optical communication (FSOC) both opto-mechatronic trends come together, especially in the space domain, where optical links need to be established between terminals hundreds (e.g. for LEO-to-ground) or ten thousands (e.g. for GEO-to-ground) of kilometers apart, using laser beams with divergences of only 10 to $100\,\mu\mathrm{rad}$. For successful fast data transfer between such terminals, absolute laser pointing accuracies of just a few $\mu\mathrm{rad}$ need to be achieved, even in the presence of vibrations and atmospheric turbulence. This introduces challenges both in the opto-mechatronic concept itself, as well as on the control design.

A. *FSOC developments at TNO*

Space-relevant FSOC is still heavily under development by many parties world-wide; Netherlands Organization for Applied Scientific Research (TNO) is contributing to these developments by designing, realizing and testing various prototype FSOC terminals for different use cases. This includes both ground stations, as well as space- and airborne terminals.

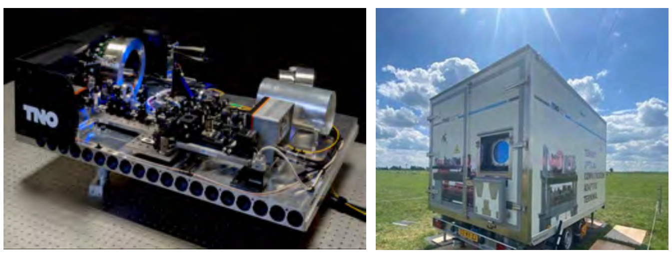

Fig. 1. The TOmCAT optical bench (left) and test trailer (right).

One of the demonstrator ground stations is TOmCAT, shown in Fig. 1, which is the outcome of a feasibility study for terabits/second feederlinks, by utilizing both AO for high-order compensation of atmospheric turbulence, and multiplexing multiple beams of different wavelength. This technology has been demonstrated in an actual field test over $10\,\mathrm{km}$, during which TOmCAT was built into a portable trailer.

Fig. 2. Ultra-Air (left) and LEOCAT (right) demonstrator terminals.

Flight hardware comes with different challenges. For example, for the airborne Ultra-Air terminal (Fig. 2, left) vibrations from the airplane it is installed in form a huge challenge to meet the extreme pointing requirements to be able to communicate with a GEO satellite $36\,000\,\mathrm{km}$ away. For space-borne terminals, such as LEOCAT (Fig. 2, right, designed for data relay between LEO satellites), the tight volume, mass and cost constraints are often the most important design drivers.

B. *The CubeCAT DTE terminal*

In this seminar talk we will discuss some technical details of another space-borne terminal, called CubeCAT, shown in Fig. 3. CubeCAT is a direct-to-earth (DTE) terminal designed for commercial cubesats and fits all its functionality in just $10 \times 10 \times 10\,\mathrm{cm}$, i.e. not only the complete optical head, but also the laser, and all electronics.

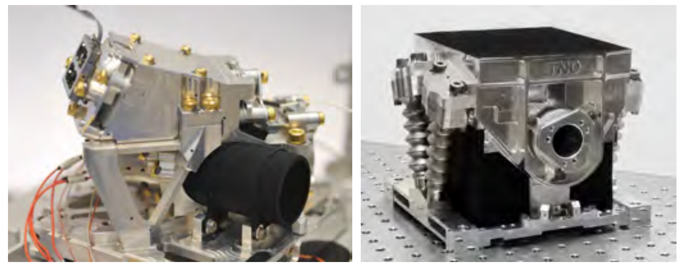

Fig. 3. The CubeCAT optical head (left) and final state before launch (right).

CubeCAT measures the angle of the incoming beacon light via a sensitive quadrant detector, and uses that information in real-time to control a Fine Steering Mirror (FSM), such that the transmitted data laser is perfectly aligned with the incoming beacon, and is thus properly pointed to the ground station. CubeCAT has been launched into orbit in April 2023, and is currently being commissioned. In this talk the opto-mechatronic design of CubeCAT will be discussed, as well as the feedback control trade-offs and verification tests.

References

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