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PhD Yearbook | 2010

Chair:
Prof. Sergio Ricci

DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

The aim of the course is the acquisition of the high level competence required to carry out innovative research and/or state of the art advanced applications in industries, public or private research centers, Universities or public and service companies in the area of aerospace engineering, including all the fields associated to it. The level of the course allows the graduates to compete in a European and international environment.

The course is three years long, requiring 180 credit points (ECTS), including possible study-abroad periods and internships in private or public institutions. The programmes and credits are divided in three main educational areas:

1. Main courses (40 credits), during the first year: courses examining fundamental subjects (problems, theories and methods) of the scientific research in the disciplinary areas involved;
2. Elective courses and training on specific themes (20 credits), gained in the second year: specific and personalised educational programs aimed at a more deep overall knowledge and to master the techniques adequate for the subsequent development of the doctoral thesis, plus seminars focused on specific and advanced methods;
3. Development of the Doctoral Thesis (120 credits): the thesis is developed within the Department or, in some cases, in other institutions, in close contact with the Department. The thesis is started immediately (20 credits in the first year), and developed in the second (40 credits) and third year (60 credits) of the doctoral program.

If the candidate has a background curriculum lacking some introductory knowledge required for the Doctorate, the Faculty will ask to recover such knowledge, with the assistance of the tutor. The same Faculty will verify afterward the overcoming of whatever was lacking during the annual meeting of admission to the second year of the course.
The course program related to point 1 does not follow a rigid scheme. So, besides widening the basic scientific culture of the candidate, it will take into consideration also the objectives and the core topics of the candidate’s thesis. Again the program outlined at points 2 and 3 will try to consider general cultural requirements as well as what is deemed to be more specifically related to thesis subject, as agreed between the candidate and the Faculty. For the activities of type 2 and 3 a study period in a foreign country is allowed, even strongly suggested perhaps. Its duration should range from a few weeks up to one and a half years. The related activities should be carried out in well known and qualified scientific institutions (universities, research centres, etc.), and well contribute to the cultural and scientific achievements of the research.

Due to the amplitude and interdisciplinarity of the aerospace sector, the professional skills achievable will span a wide area and not cover just a specific topic. The educational goals will create high level specialists in the domains of: helicopters and rotary winged vehicles, fixed winged vehicles and space vehicles.
In this context, a more specific competence can be gained either in a single or in the integration of special subjects such as: dynamics and control, fluid mechanics, systems and equipment, flight mechanics, passive structural safety, intelligent and automated systems, structures and materials.
In this respect, some examples of professional skills achieved in the course of the passed 22 years of doctoral program are here reported:

- expert in computational and/or experimental fluid mechanics, with capabilities to develop methods and models for both aerospace applications and generic vehicles;
- expert in active and passive control of the dynamics of aerospace structures, integrating global and subsystem design;
- expert in active and passive structural safety of vehicles, both aerospace and non-aerospace;
- expert in vibration and noise control, including modelling analysis, system design and implementation of specific subsystems;
- expert in the dynamics and control of aerospace vehicles and related operational missions;
- expert in integrated design of complex aerospace systems.

Since its foundation, 23 years ago, the doctoral course on Aerospace Engineering graduated more than 60 PhDs.

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BIOLOGICALLY INSPIRED CONTROL OF GRASP-LESS AND GRASPING TASKS

Franco Antonio Cavadini

In space engineering the most important and driving factor in the design of hardware and software systems is the work *environment*, whose very constraining characteristics have pushed the space engineering research towards the study and development of *Autonomous agents*. The most important feature required by such a system is the ability to dynamically change its own behaviours based on the information received from the external world, both observing and interacting with it. Looking at the example provided by humans, it is natural to focus on artificial learning in order to obtain artificial autonomous agents; for the purposes of this thesis we have identified three different types of learning: *Genetic Learning*, linked to the development of those intrinsic properties and features which are changed between generations of individuals; *Methodological Learning*, which identifies and selects the knowledge useful for the execution of future tasks; and *Executive* which changes the parameters of the system to adapt its behaviour to the specificities of the context.
The main idea at the basis of this thesis is to study the development of control systems based on the type of learning processes exposed here above.
Inside this context, we have chosen robotic manipulation as the field to which apply these concepts, because of the great interest that it has for Space applications. In particular, the contributions of this thesis are inside two specific fields:
i) *grasp-less manipulation tasks* have been studied in the context of Methodological learning because of the necessity to build internal models; and ii) the *Grasp synthesis* problem has been approached developing a control system which uses Executive Learning to adapt its behaviour to the local characteristics of the object to be grasped.
The first part of this research has proposed a control architecture to *learn* how to push an object on a table without previous knowledge about the problem; in this particular task the generation of a control action supposes two different decisions: i) choosing *where* to apply the force, and ii) identifying its *intensity*.
From a mathematical point of view, in order to push an object on a plane it is necessary to solve an inverse problem, that is, knowing the desired effects the agent must found the actions which cause that behaviour in the environment; because of the non single-valued nature of the inverse problem and taking into accounts studies on the development of the human brain, the control architecture developed in the thesis is based on the construction of internal *direct models* which are locally inverted to find the required solution. The central principle of this approach is that the ability to purposely interact with the environment is subordinate to that of predicting its evolution. This prediction task is assigned to the modules of the architecture called *Propagator* and *Anticipator*: the first one learns an internal representation of the natural dynamics of the environment, while the Anticipator predicts how the presence of an interaction changes the development of the environment with respect to its natural evolution. The reason of this approach is that, separating natural dynamics and forced variations, the two learning sub-problems are easier to solve because of their lower dimensional input domains. Both the function approximator are based on the *Locally Weighted Projection Regression* (LWPR) algorithm.
As said earlier, in order to compute the control actions an inverse problem has to be solved, but Propagator and Anticipator stores internal *direct* models of the dynamics; for this reason, it is necessary to look for the desired solution through a sampling-based procedure like a gradient descent algorithm.
The problem of this approach is its locality, meaning that (particularly in high-dimensional input spaces) the algorithm may remain stuck in a local minimum and, in general, the solution, if found, is largely dependent on the initial guess used to start the search. For this reason, a specific module has been added to the architecture, the *Prompter*, whose task is exactly to provide an initial guess for the solution search procedure; it is based on an algorithm specifically developed to mimic the characteristics of a long-term associative memory, the *Multi-Sample Hierarchical Regression* (MSHR).
Moreover, taking into consideration some studies about the functional activities of the brain during sleep, an equivalent *sleeping phase* has been introduced: the basic principle is to rely on this 'inactive' phase of the system to analyse and revise the experiences acquired during the preceding operative phase of waking, in order to organise them in a more efficient way, while eventually extracting new important information in the form of high-level dependencies between input and output variables. The group of activities executed during the sleep is collected under the name of *Meta-Learning*.
On the whole, the thesis makes the following contributions in the field of grasp-less manipulation: i) a new control architecture has been proposed and its extensive testing have proven its effectiveness in completing the object-pushing task; ii) the decomposition of the direct dynamics into its natural and forced components has be proven to be effective in making the control problem easier to solve; iii) a new algorithm, called Multi-sample Hierarchical Regression, has been developed to mimic the functions of an associative memory, allowing the direct models learning approach to be effectively used; iv) the concept of alternation between phases of waking and phases of sleep has been introduced, allowing the development of a Meta-Learning module which guarantees to obtain better performance from the controller.
The second part of the research has focused on the development of a control architecture for grasp synthesis based on the concept of synergy between the complexity of the hardware and that of the software. The grasp architecture is based on a very simple work principle: the finger of the hand which has established a contact with the object tries to maintain fixed its configuration while eventually increasing the intensity of the exchanged force if required by the specific grasping situation.
The adaptation of the contact forces is assigned to a control module based on the concept of *Executive Learning* introduced earlier; the central idea is that, when the necessity to increase the intensity of the grasp arises, the torques at the joints of the finger should be modified in order to increase only the normal component of the contact force; this is obtained thanks to the implementation of the least squares algorithm to learn a simplified model of the relationship between the variation of torques at joints and the variation of the components of the contact force.
On the whole, the thesis makes the following contributions in the field of grasp synthesis control: i) a new approach to grasp synthesis has been proposed and used to design a control architecture which is able to grasp object of arbitrary shape without using a vision system; ii) the control architecture has be proven to be suitable to accept adaptation modules based on the Executive Learning principles, specifically by implementing a Contact Controller based on the least squares algorithm;
iii) The effectiveness of the main principle introduced with this architecture has been tested and proven on the TWENDY-ONE robot at the Sugano Laboratory of the Waseda University, allowing to verify that the approach used is able to work even with the noisy characteristics of a real environment; iv) the performance of the controller has been extensively tested using a multi-body computer simulated model of a robotic hand; in particular, an alternative way of using the rolling friction parameter has permitted to verify the effects of the deformability of the skin on the stability of a grasp.

TRAJECTORY DESIGN AND OPTIMIZATION IN HIGHLY NONLINEAR ASTRODYNAMICS

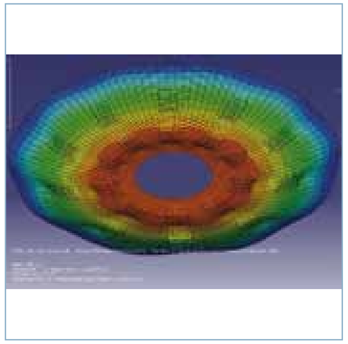
Giorgio Pietro Mingotti

The research work developed in this thesis is to be considered within the boundaries of the preliminary mission analysis, which is a key phase in space mission design. It requires the design of the transfer process through which the spacecraft is taken from a given initial orbit to a specific final one thanks to a series of controls. The standard theoretical approach to the calculation of space mission transfers is known as two-body problem, which is a simplified model of the physics of the problem. Following this model, during the navigation in a celestial-body system, the spacecraft is imagined to be under the influence of a single gravitational mass at a time; thus, navigation is conceived in terms of a sequence of spheres of influence. Within each of these spheres, the orbit of the artificial satellite is influenced by the presence of one single celestial body; in consequence, the trajectory presents all the geometric features of a conic section - which is precisely the solution to the two-body problem. Thus, whole transfers involving manifold hyperbolic passages in the proximity of celestial bodies may be seen as the union of different conic sections.
Spacecrafts are limited in terms of propellant carried on board the vehicle: this is the reason why over the last few decades trajectory design has been increasingly influenced by optimization methods whose aim is the minimization of the propellant necessary for a mission. In this way, mission specifications are tackled in terms of objective function and restricted optimization.
Following Tsiolkowsky rocket equation, the quantity of propellant necessary for a transfer is directly proportional to the energy Δv necessary to the transfer itself and, at the same time, inversely proportional to the specific impulse of the propellant considered Isp. These factors have caused the scientific community to concentrate (especially over the last decades) on the development of dynamic models meant to illustrate the physics of the problem more accurately, as well as to allow (unlike the two-body model, which is intrinsically characterized by higher energy values) the study of trajectories known as non-Keplerian, which – speaking in terms of energy - are definitely more advantageous than standard ones. Non-Keplerian trajectories are defined in n-body models, in which - since the hypothesis of Kepler's problem is violated - such trajectories can not be calculated in closed form. From a technological standpoint, the pursuit of high values of specific impulse has given rise to the development of electric engines that can continuously offer low values of propulsion. Thus, trajectory design is developed through the formulation of an optimal control method for calculating the best thrust law which should be assigned to the propulsion system.
This research stems from the awareness that trajectories designed in compliance with the principles of nonlinear astrodynamics, a relatively recent discipline whose earliest works and relevant results date back to some ten years ago, have not been fully understood in some respects. Such an underlying ambiguity in this discipline is to be ascribed to the behaviour of orbits defined in n-body models, with $n \geq 3$, which are governed by an extremely chaotic regime. In addition, a systematic study of invariant manifolds - which can be explicitly analyzed through the evaluation of the highly nonlinear intrinsic dynamics associated with the three-body problem - has recently enabled scholars to understand the leading role these manifolds play in space transfers. Most notably, these manifolds are fundamental for trajectories that, thanks to impulsive maneuvers, involve hyperbolic passages in the proximity of celestial bodies. In addition, these manifolds play a key role in trajectories which have been designed thanks to low-thrust systems. In this perspective, it is possible to formulate a theory that may describe both low- and high-energy orbits, as well as define transfers characterized by impulsive and low-thrust maneuvers. Thus, the theory of hyperbolic passages in the proximity of celestial bodies may be reformulated by means of the invariant manifolds the same way as trajectories involving Lagrangian points and low-energy transfers are usually defined.
The aim of this research activity is twofold. On one hand, there is the exploration of mathematical n-body models (with $n \geq 3$) through resorting to highly nonlinear dynamical systems; on the other, there is a combination of orbits that can be defined in this context by means of a propulsive solution characterized by continuous low-thrust values and high specific impulses. According to this approach, it is possible to work out advantageous transfer solutions in terms of the reduction of propellant on board the vehicle. In addition, it will be possible to verify from an engineering perspective the actual opportunity for the exploratory spacecraft to follow the trajectories designed in compliance with the hypotheses described above. For instance, it is necessary to verify the physical meaning of the thrust profiles calculated in relation with the possibilities made available by technology, such as the continuity of the control profile or the exposure to the sunlight of solar panels during the navigation.
The methodology elaborated in this thesis aims at merging dynamical system theory and optimal control formulation with a view of defining efficient and novel interplanetary trajectories. The guiding principle of this research is the incorporation of low-thrust into the invariant manifold technique, arising from a careful analysis of the restricted-three body problem. Thanks to this perspective, it is possible to take advantage from both flying on low energy trajectories and from having an engine with a high value of specific impulse. The low-thrust propulsion is introduced by means of *attainable sets* that are used in conjunction with the exploitation of the invariant manifold paths. The aim is to define, through a deterministic approach, accurate first guess solutions. By means of the *attainable sets*, it is possible to describe, through the same comprehensive theoretical approach, ballistic trajectories, low-thrust arcs and invariant manifolds.
Two different applicative scenarios are investigated: a Planet-to-Moon transfer and an interplanetary transfer. In details, they corresponds to the Earth-Moon and to the Earth-Mars cases. Actually, the methodology proposed is suitable for any other simple transfer within the solar system. In both applicative scenarios, two missions are proposed: transfers to low stable orbits and transfers to distant unstable orbits around the target celestial body. In details, the second mission typology is interesting for applicative and theoretical purposes. Distant periodic orbits reveal a rich phase portrait, similar to the one of periodic orbits around the Lagrangian points, which is useful to investigate through the perspective of low energy missions. As far as it concerns Earth-to-Mars transfers, three different problems are solved in one step: the ascending phase from a selected parking orbit around the Earth, the *rendez-vous* stage during the heliocentric part of the trajectory, and finally the descending and insertion into the target orbit around Mars. For both the applicative scenarios analyzed, the Earth escape stage is designed taking explicitly advantage of a lunar flyby: it is possible to plan this event in the framework of the developed Moon-perturbed Sun-Earth restricted three-body problem, discussed in this thesis. According to this approach, a significant reduction of the initial Δv is obtained. Then, the transfers are optimized within wider dynamical systems, by means of a direct method approach and multiple shooting technique, taking also implicitly advantage of the intrinsic dynamics of the n- and multi-body problems.

SMART STRUCTURES IN INSTRUMENTATION FOR ASTRONOMY

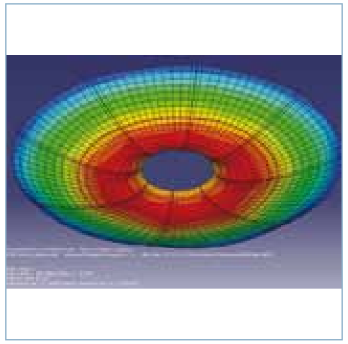
Marco Riva

This Thesis Work examine the possible porting of smart structures into the design and construction of next generation Instrumentation for Astronomy. Composite Materials are currently of relatively common use in Ground-based and specially Space-Borne Astronomical Instrumentation. However the application of smart structures is very limited and in the specific area of activated Optics has never been studied in spite of the large number of potential applications. In order to focalize the work the methodology selected of this thesis is based on the definition of a benchmark application: a spherical mirror of high surface quality with deformable curvature. Aspects such as the specific smart actuator to use, the embedding technology and the optical-quality replica process needed to manufacture the mirror have been treated in this work . Different technologies can be considered to design smart structures, in this work we have considered piezo-composites and shape-memory alloys based actuators. Most of the limitation of traditional piezoceramcis can be dealt adopting piezocomposite actuators that join piezoelectric performances of piezo-ceramic fibres to the polymer matrix making the whole system more flexible and easily conformable to curved surfaces. On the other hand, Shape Memory Alloys (SMA) are materials able to recover their original shape, after an external deformation, if heated above a characteristic temperature. If the recovery of the shape is completely or partially prevented by the presence of constraints, the material can generate recovery stress.



1. Deformable mirror actuated by piezo-composite actuators

The thesis has investigated the technological processes required for the adoption of those actuators into smart structures and some possible modeling approaches to the actuators behaviour prediction taking into account trade-offs between detailed analysis and overall performance prediction as a function of the computational time. It has been developed a combined Finite Element and Raytracing analysis devoted to a parametric optical performance predictions of a smart Piezocomposites and/or SMA based substrate applicable to deformable mirrors. The figures of merit taken into account are the active variation of the mirror focal length and the image quality. In addition a sliding mode based control system for the strongly non-linear SMA actuators has been developed

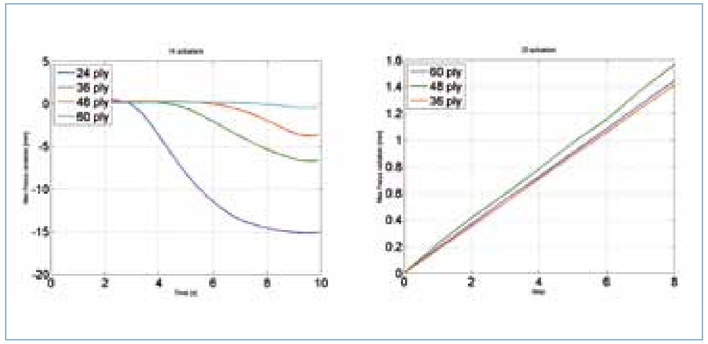


2. Deformable mirror actuated by SMA wires actuators

with numerical examples. Finally an optical quality replica process for carbon fiber reinforced plastic has been analyzed as a separate subsystem. This procedure has no influence onto the manufacturing techniques developed for smart structures because it is related to the mandrel surface and its preparation. All the phases of the process has been addressed, starting from mandrel set up to panel metrology.

The simplified modeling technique developed for piezo-composites has been validated and implemented into complex structures. The results are very interesting although obtained through light models. The investigation of this methodology completed by the Raytracing computation provided good results in terms of efficiency of mirror's shape variations respect to the image quality. Therefore this simple technology can easily deploy spherical panels able to modify their focal position of ±1,3mm. The limitation is given by the dimensions of actuators and maximum tension applicable. Future developments can surely improve those limits.

The modeling strategy developed for SMA-based smart structures adopt the lighter Turner model can for preliminary performance prediction like maximum deformed surface. The lightness of this modeling technique helps in the optimization process. The more detailed Lagoudas model can be used as a verification of the stress induced onto actuators and the variations of the transition temperatures. This procedures integrated into the combined optical and mechanical analysis has shown the partial applicability of SMA technology to CFRPbased deformable mirrors. The best compromise obtained with the material considered manifests a maximum focusing range of 2.15 mm which is quite low respect to the better MFC performances. In this case the limitation is caused by the material's phase transition characteristics. The performances obtained, even if not completely satisfying for



3. Curvature radius variation for different lamination sequence with SMA (left) and Piezo (right) actuators

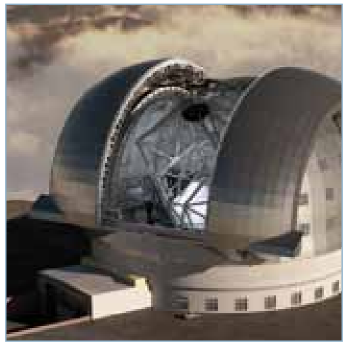
SMA smart optical devices, are very interesting for other application of SMA-based smart structures, like optical supports and actuated devices. Finally the sliding mode based control system has demonstrated that this control strategy can be efficiently adopted to manage active devices based on SMA, in particular in the case of step activation (shutter, slit carriages, ...) but also with respect to sinusoidal response (active alignment of optical elements, ...).

The replica technology developed, even if not fully compliant in terms of overall surface errors, can be fully decoupled from the actuator embedding techniques. Local surface errors have been investigated: micro-roughness and fiber print through. The most useful coating technique, which is spray coating, matches with real shape and dimension applications. The print through mitigation can be sufficiently achieved with a double curing process that a-posteriori fills the gap with liquid resin. This technology, even if with the low performances replicae, can be fully employed in minor space based astronomical applications.

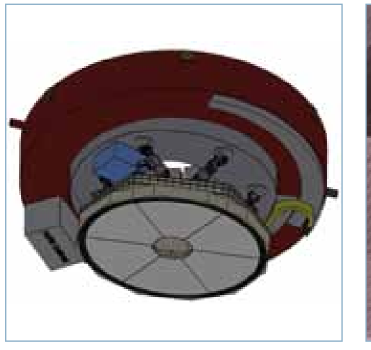
NEW MATERIALS AND TECHNOLOGIES FOR GROUND-BASED TELESCOPES: SOLUTIONS AND TECHNOLOGICAL FEASIBILITY

Matteo Tintori

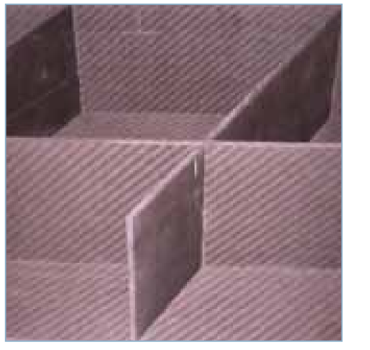
The work presented is focused on the new materials, technologies and their introduction in the ground-based astronomical engineering for the big telescopes. The introduction of these materials in the space applications in general and also for the space astronomy, had a big impact, but for the ground-based telescopes their use was not considered because the use of traditional materials and technologies has given all the benefits required. Nowadays, with the incoming of a new generation of telescopes with increased dimensions and performances, these new technologies have a fundamental role for the feasibility and functionality of these systems. The study of the thermo-mechanical characteristics of new innovative materials and their applicative technologies is focused to found solutions, strategies and methodologies adequately dealing the needs of the new generation of ground-based telescopes. The E-ELT (European Extremely Large Telescope) case was taken as a representative and important workbench.
In particular one of the main technological issue for the E-ELT is represented by its forth adaptive deformable mirror unit (M4AU). Adaptive Optics techniques allow to obtain ground-based astronomical observations comparable with the satellite based ones by compensating the effect of the atmospheric turbulence. The image quality of a telescope depends on the level of the turbulence corrections, which relies on the accuracy of the physical motions of the optical surface that performs the compensation. An adaptive telescopes optics system is usually composed by an Adaptive mirror, a Control unit and reconstructor, a Wavefront sensor and a Deformable mirror unit whose main components are a thin and deformable mirror, a series of high frequency actuators, a series of sensors coupled to the actuators, a reference body for the sensors (or Backplate), a structure on which are mounted actuators and electronics and a structure for the macro-positioning.
The best architecture for the M4AU reference body and its subsystems has been studied in detail. Two different materials have been investigated: SiC and carbon fiber composites. The position of System Engineer taken allowed to have a collaboration with ADS Int. in the frame of the M4AU preliminary design project where it was possible to study in detail the solution with the first selected material and realize some prototypes and tests. The study of the solution with the second material was developed first with the investigation of a proper geometry of the backplate and then investigating its thermo-mechanical behavior. The design with this kind of materials is not so trivial especially for complex 3D shapes, so different designs have been developed: a standard honeycomb solution and two other more complex geometry solutions. The final choice is fallen on geometry solution used for the SiC material that foresee a diamond shaped cell honeycomb structure. With this option it is possible to exchange the two material in the M4AU design without any impact on the other subsystems and interfaces.
A carbon fiber prototype has been developed to better investigate all the technological and engineering aspects and to obtain a feedback on the reliability of the developed numerical tools, to study the influences of the uncertainties of the composite manufacturing like the dimensions, the lamination sequence,... on the final unit and to highlight the possible anomalies due to the chosen technological solution.
The analysis done has shown the feasibility of both the solutions and the achievement of the specifications on the reference body. The most important technological solution aspects for the carbon fiber composite have been investigated and tested too. The numerical results agree with the mechanical and thermal tests on the prototype with a maximum error of about 15% on the sagitta and 10% on the temperatures. The thermal and mechanical analysis has also shown that a 2D model can be adequate to achieve the specifications with a low amount of error.



1. 3D of the E-ELT, courtesy of ESO



2. The adaptive unit for E-ELT, courtesy of ADS International



2. Carbon fiber composite prototype developed and tested