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# High precision massive shape control of magnetically levitated adaptive mirrors

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ABSTRACT

The paper presents a control scheme that provides precise active shape control of deformable mirror shells using a very large number of control points. The proposed controller combines a low frequency centralized feedforward and a high frequency fully decentralized feedback, with each single actuator mated to a single sensor. To grant a precisely controlled shape the feedforward part requires an accurate knowledge of the system stiffness. For this purpose a viable experimental identification procedure for high dimension steady state response matrices is described and verified through realistic simulations. Finally the control methodology is applied to the model of an adaptive secondary mirror with 3360 control points. Numerical results confirm the validity of the proposed approach.



## 1. Introduction

The resolution power of a telescope, one of its main performance indicators, is the capability to distinguish two different far away light sources. From a theoretical point of view this feature is a linear function of the optics diameter. So the trend in telescope design has been to build larger and larger mirrors. Nonetheless reality might somewhat differ from theory; large mirrors can affect the captured images by amplifying manufacturing errors and imprecisions related to restraints and assembly. Thermal deformations represent an additional problem. Moreover ground-based telescopes suffer from additional high frequency image deterioration introduced by atmospheric turbulence. In fact the image carrier is a planar electromagnetic wave that is distorted when it travels through the atmosphere because the air index of refraction is modified by the atmospheric turbulence. This effect is emphasized by large optics and represents one of the main hurdles to the successful deployment of large telescopes on the ground.

The first seminal approaches to actively compensate image distortion date back to the 1950s (Babcock, 1953), but complexity and technological limitations did not allow successful implementations. Current technological advance makes adaptive optics mature for application to Earth-based astronomical observations. The main goal of this technology is to compensate the wavefront phase distortion through the active control of the optical surface shape. The control of the whole system is quite complex and it is often structured in multilevel nested closed-loops. Successful adaptive optics, sketched in Fig. 1, comprise many components such as: a wavefront sensor, to obtain information about image distortion, a laser source, for the generation of artificial guide stars, a mirror shape generator, to compute the optimal mirror shape to correct the deteriorated wavefront, and a deformable mirror, to compensate wavefront distortions. This paper focuses on the high frequency mirror shape controller, one of the more critical components of the adaptive optics system.

An approximate idea of the number of control points needed for accurate shape control can be inferred from the simple formula $n_{cp}=\pi/4(D/r_0)^2$, where $D$ is the optical telescope diameter of the primary mirror and $r_0$ is the coherence length of the turbulence disturbance, i.e. the maximum telescope optical diameter introducing negligible aberration with respect to the wavelength of the light (Fried, 1966). The coherence length $r_0$ is proportional to $\lambda^{6/5}$, where $\lambda$ is the light wavelength. In a good astronomical site $r_0$ is about 0.13 m for a $\lambda$ of 500 nm (Racine, 2005); in the visual spectrum from violet ($\lambda=360$ nm) to red ($\lambda=700$ nm) it ranges from 9 to 20 cm, while in the near infrared ($\lambda=900-2200$ nm) it ranges from 26 to 77 cm. The most significant range of $\lambda$ for the current adaptive optics applications is 500–1600 nm, corresponding to a range of 13–52 cm for $r_0$. As a consequence for a 10 m class telescope (a telescope with a primary mirror of 10 m) the number of actuators vary in the range 4600–300; for the upcoming 30 m class extremely large telescope the number of actuators should reach the considerable values of 42,000–2600. On the other hand the minimum sampling frequency required to correct the mirror shape is linked to the characteristic time of atmospheric turbulence $t_0=0.31(r_0/\overline{v}_w)$,

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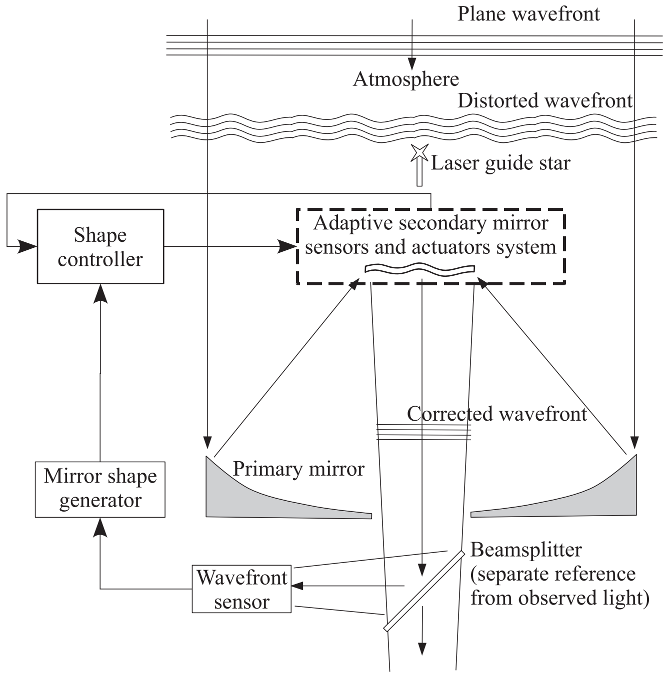


**Fig. 1.** Schematic layout of a typical secondary mirror adaptive optics system.

where $\overline{v}_w$ is the average of the turbulence velocity through the atmospheric layers (Fried, 1990; Roddier, 1999). A reasonable value for the effective wind velocity $\overline{v}_w$ can be 10 m/s, which means $t_0$ is within 4–16 ms, according to the previously mentioned $r_0$ range. So the shape command frequency should be around 1 kHz. The static precision required for the deformed mirror shape is within few tens of nanometers at most, with overall deformations up to some micrometers (Hardy, 1998).

An adaptive correction can be obtained through the use of continuous or segmented mirrors. The segmented solution was considered the simplest one for the initial applications (Freeman & Pearson, 1982), but adaptive optics evolution decreed a sort of supremacy of continuous mirrors in terms of trade-off between performances, cost and complexity, see Roddier (1999) or Hardy (1998) for more details. The actuation of flexible mirrors can be obtained in different ways. An accurate classification is not straightforward because, starting from the 1970s, many different solutions have been proposed and developed. A taxonomy could be built intersecting the three main philosophies of continuous facesheet mirror construction, i.e. monolithic, discrete array and bimorph, and the main actuation technologies, i.e. piezoelectric–electrostrictive, electrostatic and electromagnetic. For example the first deformable mirror installed on a ground-based telescope was monolithic piezoelectric (Hardy, Lefebvre, & Koliopoulos, 1977), while the stacked piezoelectric actuated mirrors have been the most widely used in the 1990s (Rousset et al., 1663; Wirth, Landers, Trvalik, Navetta, & Bruno, 1995). A deformable piezoelectric bimorph mirror has been first applied by Roddier, Anuskiewicz, Graves, and Roddier (1994) and remains a viable solution (Rodrigues et al., 2009). The electrostatic actuation, adopted with MEMS, (Dagel et al., 2006; Durr, Honke, Alberti, & Sippel, 2003), has been used for reflective membrane mirrors as well (Takami & Iye, 1994).

A fundamental step in adaptive optics evolution is represented by the introduction of the concept of secondary deformable mirror, together with the idea of using non-contacting voice-coil actuators (electromagnetic discrete array solution), co-located to capacitive position sensors (Salinari, Del Vecchio, & Biliotti, 1993). An implementation of this design proved its effectiveness on an already operating secondary with 336 control points, mounted on the Multiple Mirror Telescope (MMT, Riccardi et al., 2001). A further realization, currently close to operation, is the Large Binocular Telescope (LBT) with 672 control points (Riccardi et al., 2003). The same technology, but with 1170 actuators, will be applied to the Very Large Telescope (VLT), which is now in the manufacturing phase (Strobele et al., 2006). The Giant Magellan Telescope (GMT) deformable secondary mirrors should exploit the same adaptive system through 4620 actuation points (Lloyd-Hart, Angel, Milton, Rademacher, & Codona, 2006). The same kind of solution is under evaluation for application on the M4 unit of the European Extremely Large Telescope (E-ELT), where the number of control points should grow over 6000 (Strobele et al., 2008; Vernet et al., 2008). Note that other actuation technologies, not discussed in this paper, are being actively studied for massively actuated mirrors (e.g. Andersen et al., 2006; Hamelinck et al., 2008).

Electromagnetic voice-coil actuators are non-contacting, and have null stiffness. Their pros and cons can be better understood by comparing them with actuator types that are connected to the mirror shell and have a relatively high intrinsic stiffness, e.g. piezostacks. Stiff actuators feel a thin mirror as a minor disturbance and thus have a small cross-talk effect induced by the mirror. However, the connection of the actuators to the mirror inevitably implies some kind of over constraining. The need to avoid the introduction of excessive local assembly distortions that will be difficult to be actively corrected afterward makes this connection difficult to design. On the contrary, magnetically levitated non-contacting actuators have no connection problems but are strongly coupled through the mirror shell, making punctual positioning impossible without caring of all the others. This strong coupling heavily affects the dynamics and the control of the system. As soon as this problem is overcome the adoption of non-contacting actuators brings further advantages, including the possibility to operate with failed control points, with minor degradation of positioning performances, without any maintenance intervention (Lloyd-Hart et al., 2003; Wildi et al., 2003).

Obviously the design of a shape control system for deformable structures with dimensions in the order of meters, with many thousands of control points, is a significant challenge. The capability of existing control systems to scale up to so many control points must be carefully evaluated. In fact, systems adopting the secondary deformable mirror solution, significantly the E-ELT, will excite high density, high frequency structural vibration modes, thus requiring a high control bandwidth to ensure stability and an adequate dynamic behavior. The intrinsically coupled nature of the problem suggests a centralized controller, but the complexity of the solution and the time needed to acquire, condition and process all the control units' signals hinder its adoption. A more viable approach is based on a decentralized solution, or a partially decentralized one. Many papers deal with centralized and/or partially decentralized feedback control of large distributed systems, e.g. Baudouin, Prieur, Guignard, and Arzelier (2007), Bamieh, Paganini, and Dahleh (2002), D'Andrea and Dullerud (2003) and Gorinevsky and Stein (2003), see also references thereof. Partially decentralized controllers have been proposed to handle papermaking (e.g. Stewart, Gorinevsky, & Dumont, 1998), thermal processes and semiconductor manufacturing. The same techniques have been suggested for the control of large reflective surfaces, with potential applications in active and adaptive optics (Gorinevsky, Boyd, & Stein, 2003; Kulkarni, D'Andrea, Brandl, Wizinowich, & Bonaccini, 2003; Stein & Gorinevsky, 2005).

A different solution was adopted for the MMT and LBT control scheme, combining a low frequency partially centralized feedforward