# ELT M4 Adaptive Mirror Actuator: Magnetic Optimization and Future Developments

C. Del Vecchio[1] R. Briguglio[1] M. Xompero[1] A. Riccardi[1]
G. Agapito[1] S. Barmada[2] L. Sani[2] R. Biasi[3] D. Gallieni[4]

[1]INAF–OAA, Firenze, Italy [2]DESTEC–Unipi, Pisa, Italy [3]Microgate, Bolzano, Italy
[4]ADS International, Valmadrera (LC), Italy

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# Outline

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1. Rationale
   - AO Principle
   - Motivation
2. Statics
3. Dynamics
   - Open-loop
   - Closed-loop

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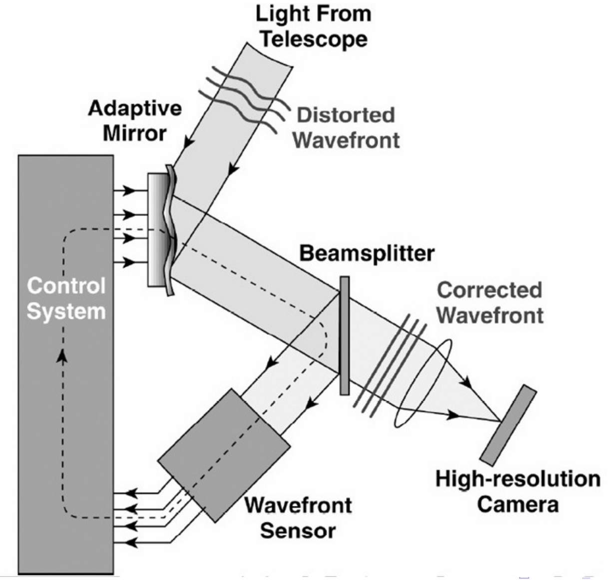
# Compensating the Atmospheric Turbulence

## The Control System Concept



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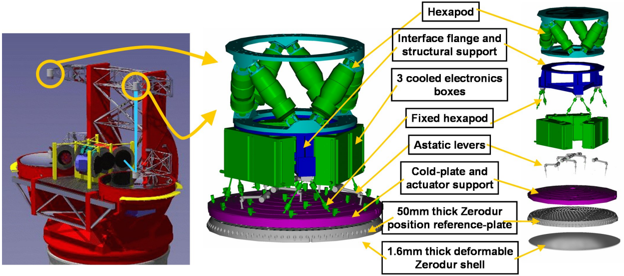
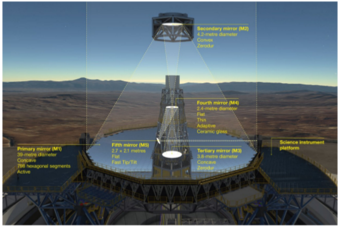
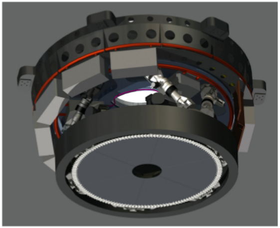
# Adaptive Optics on board the Telescope

## From .911/8.4m [Riccardi et al., 2004] to 2.6/39.3m [Vernet et al., 2012]

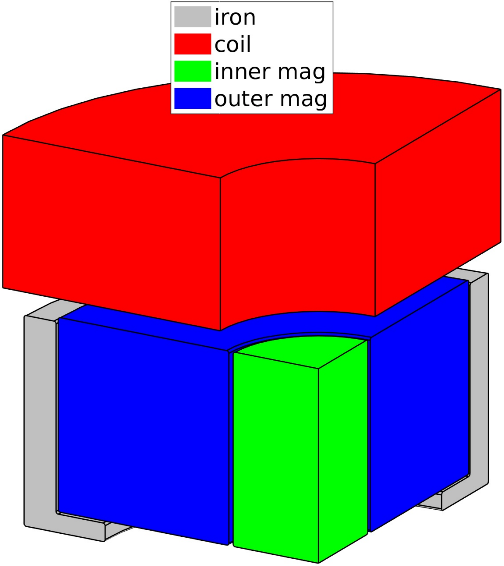


# The Device

## The Magnetic Circuit of the Voice-Coil Actuator



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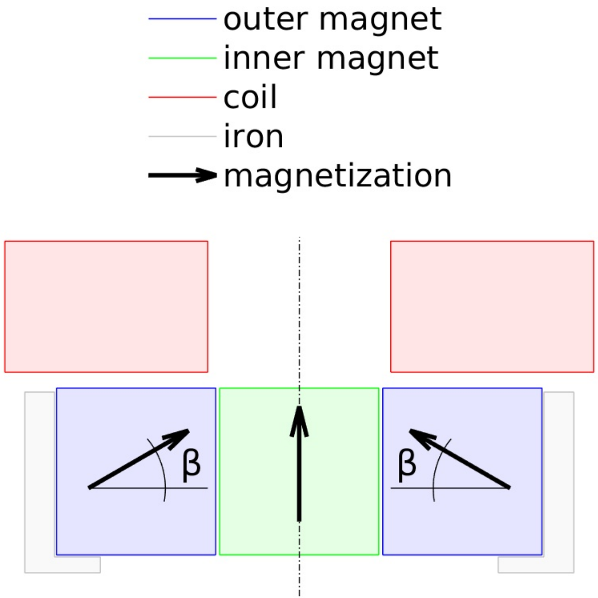


# The Real Actuator

## The Specs

| | |
|---|---|
| outer mag radii | 2.1 mm and 6.1 mm |
| inner mag radius | 2 mm |
| mag height | 4.2 mm |
| coil radii | 2.3 mm and 7.4 mm |
| coil height | 3.3 mm |
| rms force (turbulence correction) | 0.363 N |
| max force (static) | 0.36 N |
| max force (dynamic) | 1.27 N |
| stroke (mechanical) | $\pm$200 µm |
| gap (magnet-to-coil) | 400 µm |
| bandwidth | 1 kHz |
| typical inter-actuator spacing | 26 mm |
| typical mobile mass | $\lesssim$10 g |

# The Driving Parameter
## The Efficiency Definition

*The driving parameter* $\varepsilon = \dfrac{F}{\sqrt{P}}$

$$\varepsilon = \sqrt{2\pi \frac{\gamma}{\rho} \frac{S}{\overline{R}}} \;\; \Psi$$

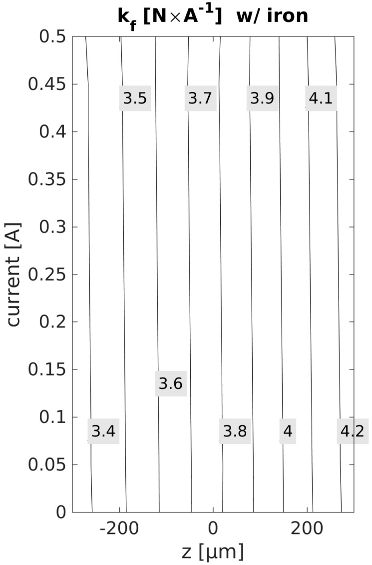
$$\Psi = \frac{\int_S B_r \; r \; dA}{S} \qquad \gamma = \frac{N \pi r_{wire}^2}{S}$$

*The force function* $K_f = \dfrac{F}{I}$

$$K_f = N \; 2\pi \; \Psi$$

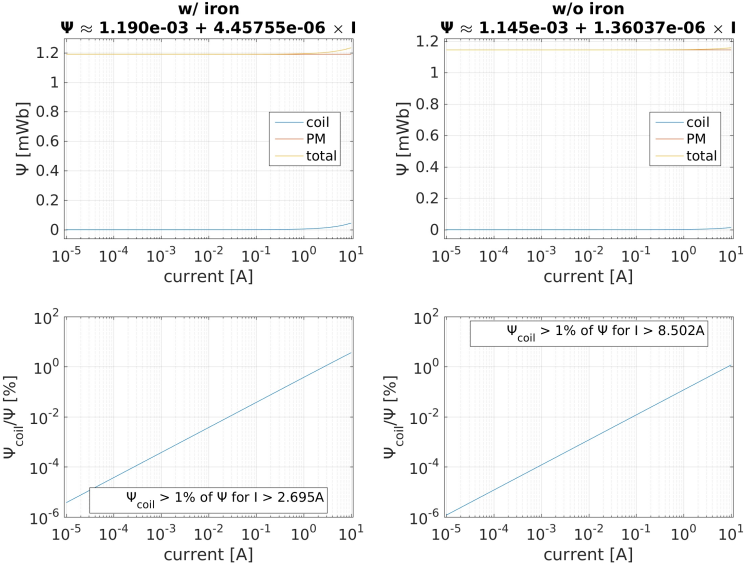
# The preliminary Results

$\epsilon = \epsilon(I, z)$ and $K_f = K_f(I, z)$



# The preliminary Results

## $\epsilon = \epsilon(I, z)$ and $K_f = K_f(I, z)$



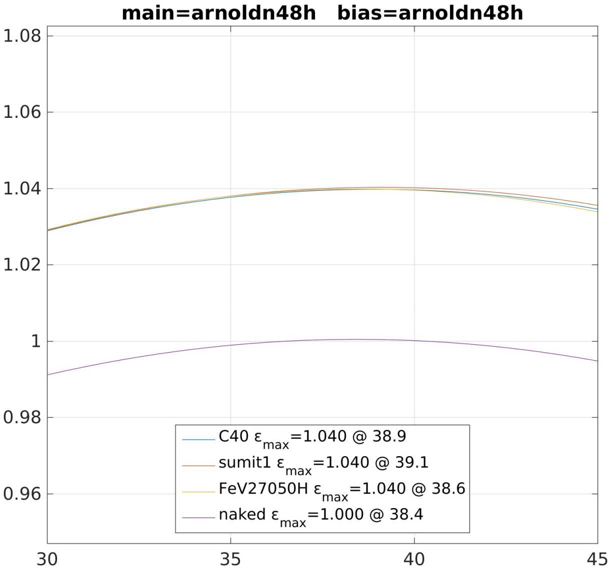
# The preliminary Results

## $\epsilon = \epsilon(I, z)$ and $K_f = K_f(I, z)$

$$\text{if } I <= 1, \quad \Psi = \text{const} \rightsquigarrow \epsilon \text{ and } K_f \text{ are constants}$$

# Optimization: $\epsilon = \epsilon(\beta, q_i, q_p)$

## What Affects What, with and without Iron



# Optimization: $\epsilon = \epsilon(\beta, q_i, q_p)$

## What Affects What, with and without Iron

| parameter | range | result |
|---|---|---|
| $\beta$ | from 30° to 45° | ✓ |
| $q_i$ (PM material) | 3 types | $\frac{\partial \varepsilon}{\partial q_i} \approx 0$ |
| $q_i$ (iron material) | 3 types | $\frac{\partial \varepsilon}{\partial q_p} \approx 0$ |

# Optimization: $\epsilon = \epsilon(\beta, q_i, q_p)$

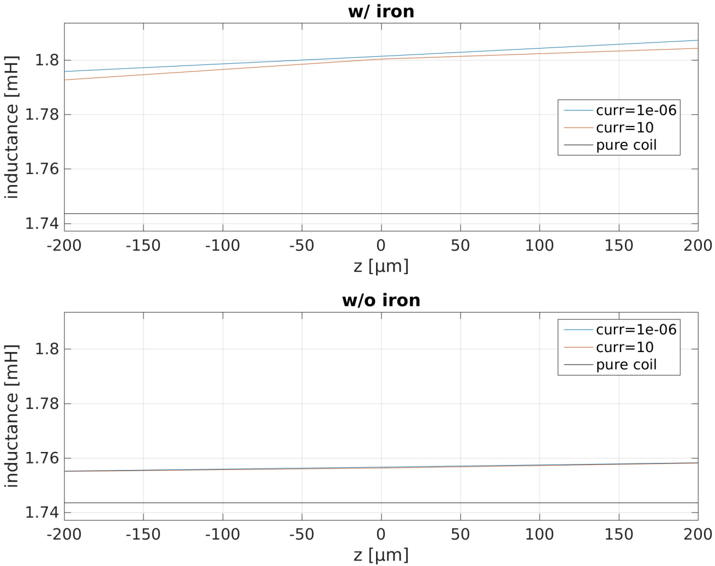
## What Affects What, with and without Iron

### *Optimization outcome*

- $\dfrac{\partial\varepsilon}{\partial\beta} = 0$ @ $\beta = 38.2^\circ$ to $38.7^\circ$
- $\varepsilon \geq 1\,\mathrm{N\,W}^{-1/2}$ with most materials
- Adding the iron pot increases $\varepsilon$ by few %

# A By-product of Statics

## Computing Inductance as $\frac{d\lambda}{dI}$



# A By-product of Statics

## Computing Inductance as $\frac{d\lambda}{dI}$

### *Inductance*

- $\frac{\partial L}{\partial z} \approx 0$
- $\frac{\partial L}{\partial I} \approxeq 0$
- $L$ increases by few % wrt 1.742 mH (inductance of bare coil)

# A *real* Simulation

## Modifying the *Static* Model to Get the *Dynamic Model*

statics

$+$

ode's $+$ deformable mesh $+$ coil current $I = I(t)$

$\Downarrow$

dynamics

$\downarrow$

$$F = m\ddot{x} + c\dot{x} + kx$$

$$\frac{d\lambda_Q}{dt} = \frac{Q}{I}$$

$$\lambda = \lambda_c + \lambda_Q$$

$\lambda_c$ defined as $2\pi \frac{N}{S} \int_S A_\varphi r dS$ in the next slide

# Obtaining a *real* Physics

## Modifying a Comsol Definition

| $P_{inp}$ | | | |
|---|---|---|---|
| $P_{Cu}$ | $P_{Fe}$ | $P_{mag}$ | $P_{iner} + P_{vis} + P_{spr}$ |
| $I^2R$ | $Q = \int_{V_{Fe}} \mathcal{J}_{Fe}^2 \rho_{Fe} dV$ | $LI\frac{dI}{dt}$ | $P_{kin} = K_b \frac{dz}{dt} I = K_f I \frac{dz}{dt}$ |
| $I^2R$ | $V_{ind} I$ | | |

$$V_{ind} = \frac{Q}{I} + L\frac{dI}{dt} + K_b\frac{dz}{dt} = V_Q + \frac{d\lambda}{dt}$$

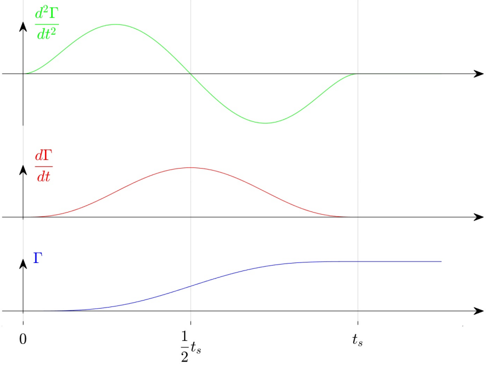
| | |
|---|---|
| $\lambda = 2\pi \frac{N}{S} \int_S A_\varphi r dS$ | $\equiv$ comsol definition |
| $V_Q = \frac{2\pi}{I} \int_{S_j} \mathcal{J}_\varphi E_\varphi r dS$ | to be added into comsol |

# Outline

# A suitable Step Function

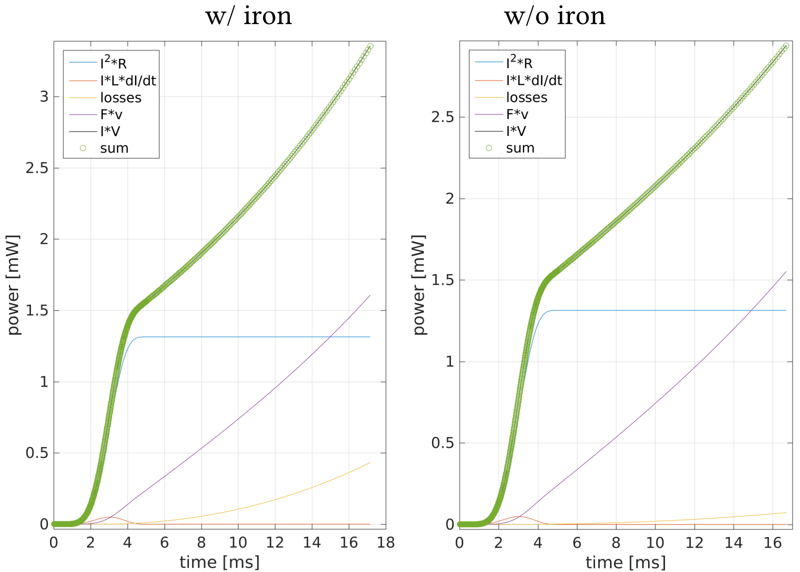
## Making the *Step* continuous up to its 4th Derivative

$$\Gamma(t) = \begin{cases} \dfrac{t^4\left(20\,t^3 - 70\,t^2\,t_s + 84\,t\,{t_s}^2 - 35\,{t_s}^3\right)}{-{t_s}^7} & \text{if } 0 \le t \le t_s \\ 1 & \text{if } t > 0 \end{cases}$$



# Preliminary Runs

## Validating the Implementation: $I(t) = I_0\Gamma(t)$, with $t_s = 5\,\text{ms}$, $I_0 = 10\,\text{mA}$



# Preliminary Runs

## Validating the Implementation: $I(t) = I_0\Gamma(t)$, with $t_s = 5\,\mathrm{ms}$, $I_0 = 10\,\mathrm{mA}$

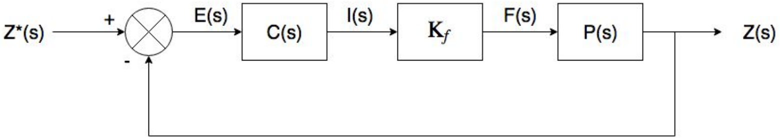
### The open loop outcome

- The Power Balance Is Satisfied
- iron-type losses wrt to total power @ $3.8\,\mathrm{mm\,s^{-1}}$
  - 12.9% w/ iron
  - 2.5% w/o iron

# Outline

# Closed Loop Implementation

## Data from Statics and Matlab trial-and-error Run




$$\epsilon(t) = z^{\star}(t) - z(t) \qquad z^{\star} = z_s\,\Gamma(t)$$

| | | |
|---|---|---|
| $C(s)$ | $K_p + sK_d + \frac{1}{s}K_i$ | $I(t) = K_p\epsilon(t) + K_d\frac{d\epsilon(t)}{dt} + K_i\int_0^t \epsilon(t)\,dt$ |
| $P(s)$ | $(m+m_o)\,s^2 + cs + k$ | $(m+m_o)\frac{d^2z}{dt^2} + c\frac{dz}{dt} + kz$ |

# Closed Loop Implementation

## Data from Statics and Matlab trial-and-error Run

| | | |
|---|---|---|
| $t_s$ | $0.8\,\mathrm{ms}$ | settling time |
| $z_s$ | $1\,\mu\mathrm{m}$ | set point |
| $K_f$ | $3.547\,\mathrm{N\,A^{-1}}$ | force constant |
| $K_p$ | $3.5\times10^{-7}\,\mathrm{A\,m^{-1}}$ | proportional gain |
| $K_d$ | $600\,\mathrm{A\,s^{-1}\,m^{-1}}$ | derivative gain |
| $K_i$ | $1\times10^{10}\,\mathrm{A\,m^{-1}\,s^{-1}}$ | integral gain |
| $m$ | $5.003\times10^{-3}\,\mathrm{kg}$<br>$3.787\times10^{-3}\,\mathrm{kg}$ | mobile mass[1]<br>mobile mass[2] |
| $m_0$ | $1\times10^{-3}\,\mathrm{kg}$ | glass mass[3] |
| $c$ | $10\,\mathrm{N\,s\,m^{-1}}$ | damping coefficient[4] |
| $k$ | $1\times10^{6}\,\mathrm{N\,m^{-1}}$ | glass stiffness[3] |

(1) w/ iron

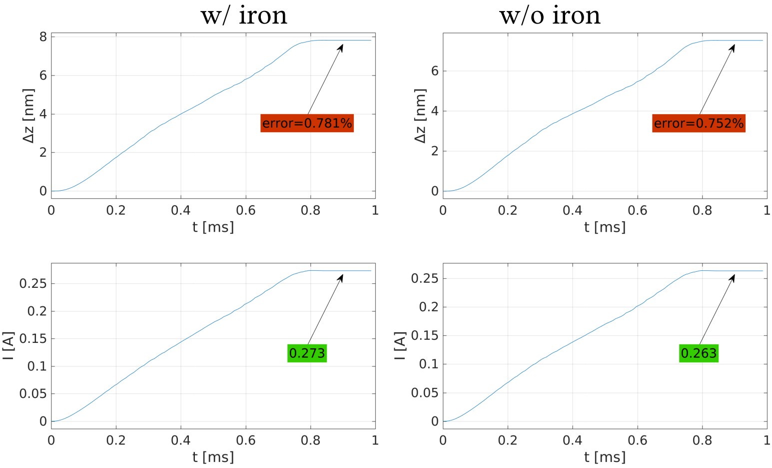
(2) w/o iron

(3) typical

(4) air gap

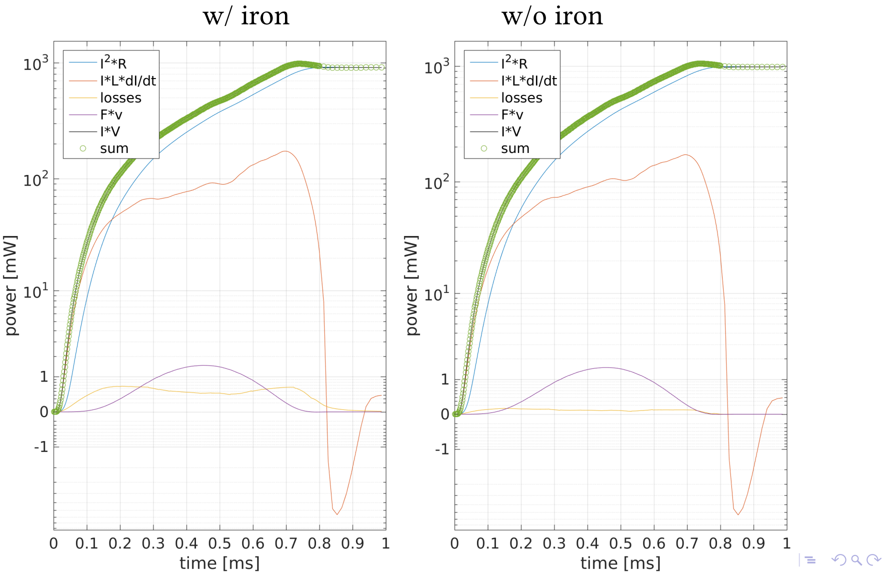
# Closed Loop Results

## The Current and Position Responses



# Closed Loop Results

## The Power Budget



# Closed Loop Results

## The Basis for the Up-coming Dynamics

**The closed loop outcome**

- The Actuator Supplied the Requested Stroke within the Requested (Short!) Time
- the max iron-type losses wrt to total power are small
  - 2.5% w/ iron
  - 1.2% w/o iron

# Lessons Learned

INAF - Arcetri

### *Upgrading the existing actuator*

- Modifying the magnetization direction allows to increase the efficiency by $\approx 20\%$
- Providing good PM's and soft irons, the efficiency doesn't depend on the materials
- The iron pot weakly affects the efficiency

# Lessons Learned

### *A crucial requirement*

The total power dissipation has to be properly considered in the power budget

THIS COMPUTATION IS CORRECT IF

**Some comsol default definitions are modified**

# Lessons Learned

## *The good result*

- a full closed-loop dynamic response is available via
  - some ode's
  - the deformable mesh

A very simple PID gives a 1 μm stroke in 0.8 ms

# Future Work

**Even if the design of the control system is beyond the aim of this talk, Comsol can manage any equation**

*The next steps*

Given *any* control design, a method to determine the closed/open loop dynamic response is available

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**Even if the design of the control system is beyond the aim of this talk, Comsol can manage any equation**

*The next steps*

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# For Further Reading I


- Riccardi, A., Brusa, G., Xompero, M., Zanotti, D., Del Vecchio, C., Salinari, P., Ranfagni, P., Gallieni, D., Biasi, R., Andrighettoni, M., Miller, S., and Mantegazza, P. (2004).
The adaptive secondary mirrors for the Large Binocular Telescope: a progress report.
In Bonaccini Calia, D., Ellerbroek, B. L., and Ragazzoni, R., editors, *Advancements in Adaptive Optics*, volume 5490 of *Proc. SPIE*, pages 1564–1571. SPIE.

- Vernet, E., Cayrel, M., Hubin, N., Mueller, M., Biasi, R., Gallieni, D., and Tintori, M. (2012).
Specifications and design of the E-ELT M4 adaptive unit.
In *Adaptive Optics Systems III*, volume 8447, pages 8447 – 8447 – 8. SPIE.