Presented at the COMSOL Conference 2010 Paris

Modeling VRALA, the Next-Generation Actuator for High-Density, Tick Secondary Mirrors for Astronomy

Comsol for Adaptive Optics

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Outline

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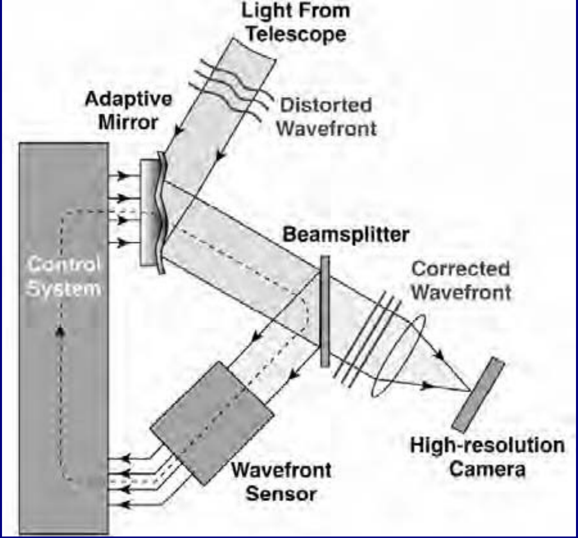
1. Background
   - The AO Principle
   - The Design Drivers
2. Statics
   - The Approach
   - The Model
3. Dynamics
   - The Governing Equations
   - The Open-Loop Response
   - The Closed-Loop Response

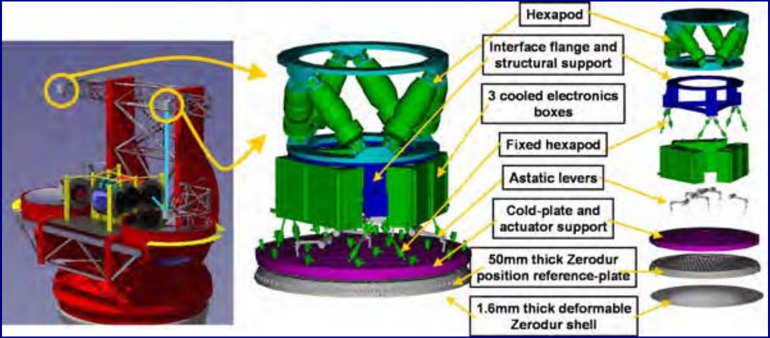
Compensating the Atmospheric Turbulence

The Control System Concept



Adaptive Optics on board the Telescope

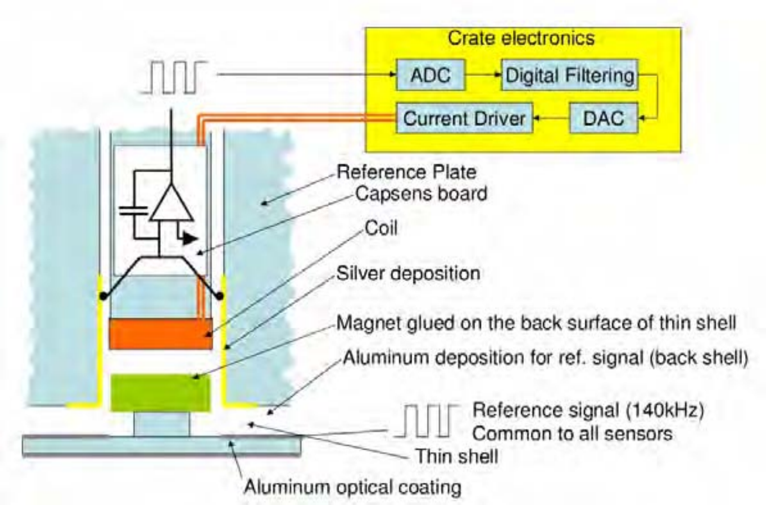
System Overview



[Riccardi et al., 2004]

Actuating the DM & Sensing the Displacements

The LBT Voice-Coil Actuator



Outline

Basic Requirements of High Order DM's

The Specs are very Severe

rms force (turbulence correction)	$.363\,\mathrm{N}$
max force (static)	$.36\,\mathrm{N}$
max force (dynamic)	$1.27\,\mathrm{N}$
stroke (usable)	$\pm 100\,\mu\mathrm{m}$
stroke (mechanical)	$\pm 150\,\mu\mathrm{m}$
bandwidth	$1\,\mathrm{kHz}$
typical inter-actuator spacing	$25\,\mathrm{mm}$
typical actuator length	$\leq 60\,\mathrm{mm}$
typical mover mass	$\leq 10 \times 10^{-3}\,\mathrm{kg}$
DC resistance	$2 \text{ to } 2.5\,\Omega$

DM Stiffness vs. DM Thickness & Act Spacing

The Plate Stiffness is Strongly Non-Linear

The plate stiffness

$$K_{flex} \propto t^3 \times (1/d)^4$$

t = thickness d = dimension

- What if
  - the inter-actuator spacing is slightly reduced
  - the thickness is slightly increased

$$\left.\begin{array}{ll} \text{HIGHER ORDER DM} & d = 30 \rightarrow 25\,\mathrm{mm}\ (16\%) \\ \text{ELT PANELS} & t = 1.6 \rightarrow 2\,\mathrm{mm}\ (20\%) \end{array}\right\} \rightsquigarrow 2{\times}K_{flex}$$

The Design Criterion: Avoid Thermal Pollution

The (*usual*) Basic Question and the (*enhanced*) Answer

reduce the *local seeing*

⇓

reduce any local heating

⇓

given the force, reduce the power

⇓

maximize the efficiency

(the force-to-power ratio)

WHILE

♣ respecting the geometry

♣ minimizing the emi

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The Electromagnetic Core

Variable Reluctance LM: $F = \int_S -\frac{1}{2}(\mathbf{H}\cdot\mathbf{B})\,\mathbf{n} + (\mathbf{n}\cdot\mathbf{H})\,\mathbf{B}^T\,dS$

[Del Vecchio et al., 2010]

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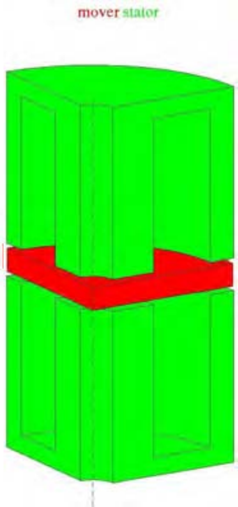

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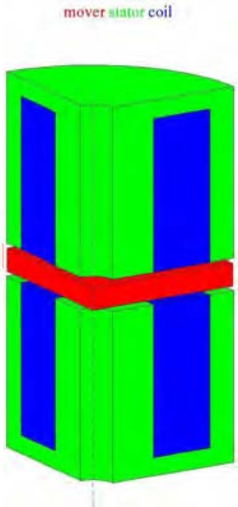


[Del Vecchio et al., 2010]

Outline

The Full Coil Approximation

The Filling Factor φ Dramatically Reduces the DOF's

Static

$$R_f = \frac{\varphi}{N^2} R$$

$$J_f^2 = \varphi J^2 = \varphi \left(\frac{I}{A_w} \right)^2$$

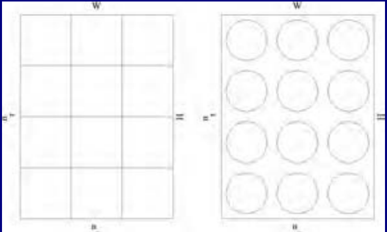
$$F_f = \frac{1}{\varphi} F$$

$$\overline{V}_f = \frac{\sqrt{\varphi}}{N} V$$

Transient

$$J_f = N \frac{I}{A_w}$$

$$\overline{V}_{ind_f} = N \overline{V}_{ind}$$



The Numerical Optimization I

A Single Matlab Script to Fully Calculate the Magnetic Response

geometry define the (very simple!) basic components in the r-z plane

meshing get the elements (typically 10000) and embed them in the *azimuthal currents* application mode

physics define

- the physical properties of the chosen materials (via tables or plots provided by the manufacturers), including the air
- the input external current density (with the proper correction factor)

solution solve the non linear system (of typically 20000 equations) for A_φ

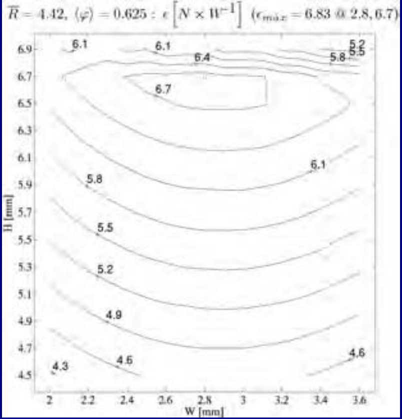
post-proc. compute the magnetic force via the Maxwell stress tensor (multiplying by φ)

The Numerical Optimization II

Materials & Geometry: $\epsilon_{max} \approx 7\,\mathrm{N} \times \mathrm{W}^{-1}$

mat 64% of 17 × 17 combinations $\rightsquigarrow \epsilon \geq 6\,\mathrm{N} \times \mathrm{W}^{-1}$

geom $\epsilon = \epsilon\left(h_{mov}, r_{stat_o}, W, H, \overline{R}\right) \mapsto \epsilon = \epsilon\left(W, H, \overline{R}\right)$



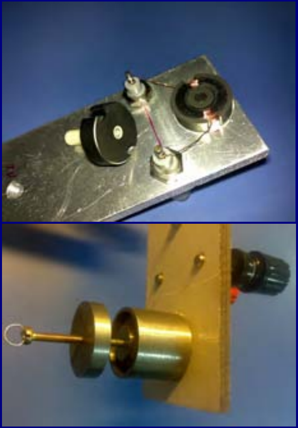
$\overline{R} = 4.42$, $\langle\varphi\rangle = 0.625$: $\epsilon\left[N \times W^{-1}\right]$ ($\epsilon_{max} = 6.83$ @ 2.8, 6.7)

Iron losses $\leq$ 1.6% of the DC power, via frequency analysis

The Numerical Optimization III

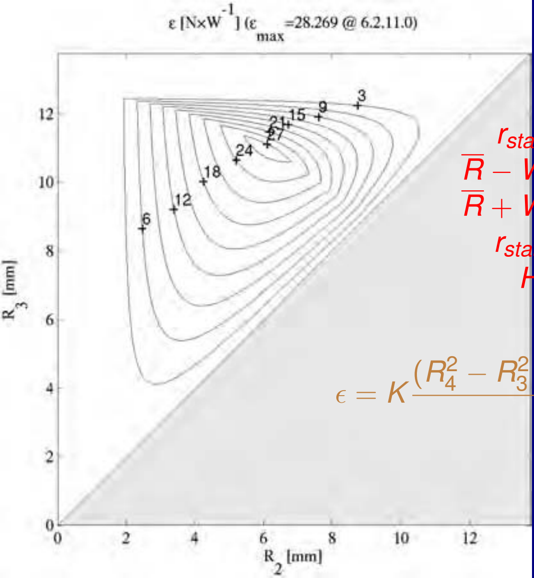
Prototypes: the Magnetostatics results are experimentally confirmed

value	Pure Fe	Ferrite
R_1 [mm]	1.5	1.5
R_2 [mm]	6	4.5
R_3 [mm]	11	9
R_4 [mm]	12.5	10.75
h [mm]	12	5
turns	400	85
force [N]	1.95	0.71
voltage [V]	1	0.75
current [A]	0.2	0.8
power [W]	0.2	0.6
ϵ [$N \times W^{-1}$]	9.75	1.18



The Analytical Optimization

The Comsol Results Match the Analytical Ones



$r_{stat_i} \hookrightarrow R_1$

$\overline{R} - W/2 \hookrightarrow R_2$

$\overline{R} + W/2 \hookrightarrow R_3$

$r_{stat_o} \hookrightarrow R_4$

$H \hookrightarrow h$

$$\epsilon = K\frac{(R_4^2 - R_3^2 + R_2^2 - R_1^2)(R_3 - R_2)}{R_3 + R_2}$$

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Setting Up the Model

The Full Coil is Implemented Multi-Physically

- $$\underbrace{A_\phi}_{\mathrm{m/s}} \otimes \underbrace{r, z}_{\mathrm{ALE}} \otimes \underbrace{F = (M + m_0)\ddot{z}}_{\mathrm{ODE}} \otimes \underbrace{(V_{ext} - V_{ind})/R}_{\text{coupling eq}}$$

  where $V_{ext} = I_{ext} R \qquad I_{ext} = \sqrt{\varphi}\frac{A}{A_w}$

- $$\overline{V}_f = \int_A \frac{(-e_f + J_f \rho) 2\pi r}{A} dA$$

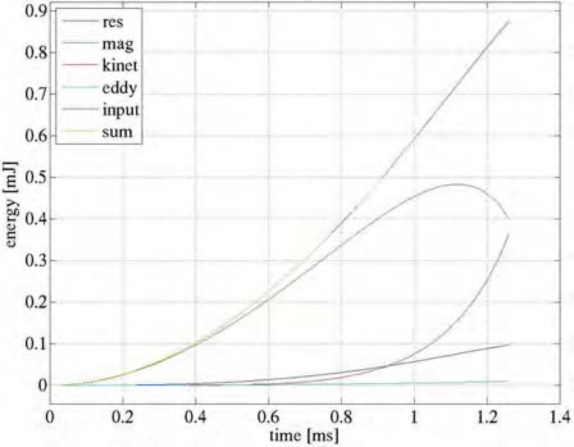
  where $\int_A \frac{e_f 2\pi r}{A} dA$ is $\overline{V}_{ind_f}$

Outline

The Electromagnetic Inertia

Energy Balance

$$P(t) = Vi(t) = \underbrace{P_{Fe} + P_{Cu}}_{P_{heat}} + P_{magn} + P_{kinet}$$



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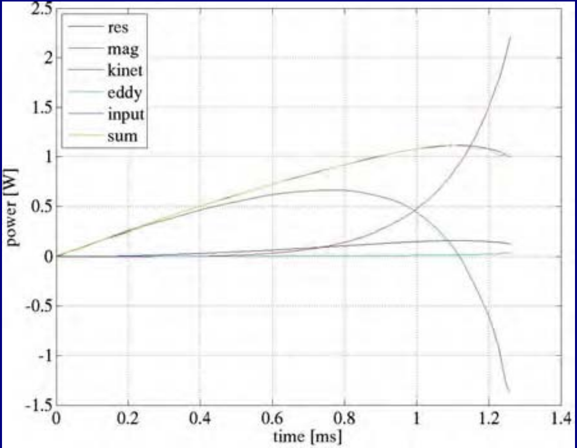

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The *stored* magnetic energy

$$P_{magn} = \int_V \left(\int_0^B H\,dB \right) dV$$

defined via Comsol *functions*
after Matlab numerical integration

$$P_{heat} \ll P \quad \Rightarrow \quad P \approx \begin{cases} P_{magn} & \text{for } t \leq .8 \\ P_{magn} + P_{kinet} & \text{for } t > .8 \end{cases}$$

The e/m inertia is a big issue for the control system

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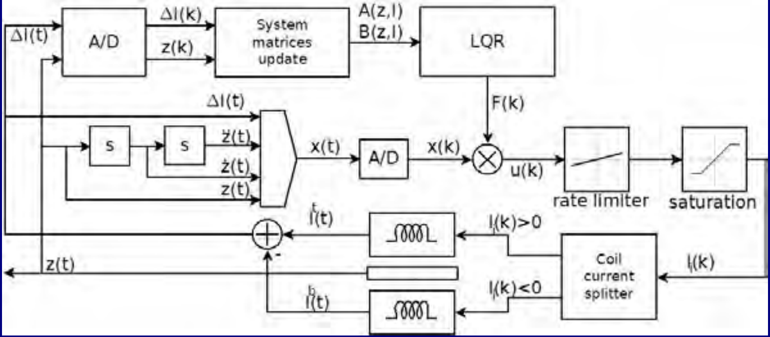
The Real-Time-Updating LQR I

The Block Diagram



The Real-Time-Updating LQR II

Design Principles

- the state x is defined as $x(k) = [\, I(k)\, \ddot{z}(k)\, \dot{z}(k)\, z(k)\,]'$ (sampling @ $50\,\mathrm{kHz}$ at each p_k)
  - I = current signal
  - z = position feedback ($z \Rightarrow \dot{z} \Rightarrow \ddot{z}$)
- at each k step, the *system matrices update* determines $A(p)$ and $B(p)$ in $x(k+1) = \mathbf{A}(p)x(k) + \mathbf{B}(p)u(k)$
  - $\begin{matrix} A(p) \mapsto \\ B(p) \mapsto \end{matrix} \boxed{\boxed{\text{LQR}(\text{p},\lambda)}} \mapsto F(k)$ (control matrix)
- 2 limits: $|I_i| \leq I_{max}$ & $\left|\dfrac{dI_i}{dt}\right| \leq dI_{max}$
- $I_i \mapsto \boxed{\text{coil current splitter}} \mapsto \begin{cases} I_i^t \text{ if } I_i > 0 \\ I_i^b \text{ if } I_i < 0 \end{cases}$

λ is the forgetting factor, according to RLS theory

The Real-Time-Updating LQR III

The 2 Transfer Functions

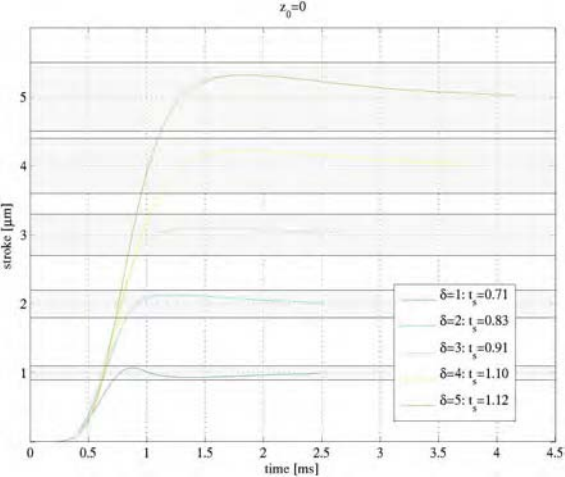
The plant is the combination of 2 TF's

1. $F = f(z, I)$, non linear, but linearized @ $p = (\bar{z}, \bar{I})$ by $f(z, I) \approx k(p) + k_z(p)\delta z + k_I(p)\delta I$
    - $k(p) = f(p)$
    - $k_z(p) = \left.\frac{\partial f(z,I)}{\partial z}\right|_{(p)}$
    - $k_I(p) = \left.\frac{\partial f(z,I)}{\partial I}\right|_{(p)}$
2. $\frac{I(s)}{I_i(s)} = \frac{1}{\omega s+1}$, a first order low-pass filter
    - ω is the time constant
    - $I(s)$ is the Laplace transform of the coil current
    - $I_i(s)$ is the Laplace transform of the input current

The Closed-Loop Results

The Step Response

$z_0 = 0; \delta = 1$ to $5\ \mu\text{m}$

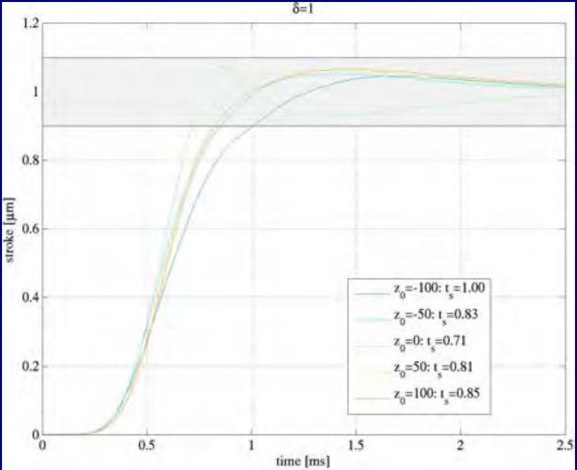


t_s for $\delta = 4$ and $5\ \mu\text{m}$ exceed by 10% the goal

The Closed-Loop Results

The Step Response

$z_0 = -100$ to $100\ \mu\mathrm{m};\ \delta = 1\ \mu\mathrm{m}$

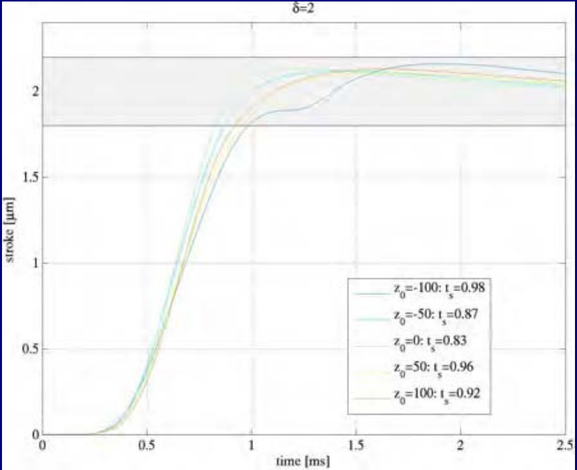


$\boxed{t_s \leq 1\ \mathrm{ms}}$

The Closed-Loop Results

The Step Response

$$z_0 = -100 \text{ to } 100\ \mu\text{m};\ \delta = 2\ \mu\text{m}$$



$$\boxed{t_s \leq 1\ \text{ms}}$$

The Closed-Loop Results

The Step Response

The maximum average power computed over the entire time domain ranges from 1.3 to 10.7 mW

Lessons Learned & Future Work

A challenging project

The high-order, long-stroke, very large deformable mirrors of the next generation telescopes require very large forces and unprecedented actuator densities. The simple and very effective magnetic circuit of VRALA is well-suited to accomplishing this goal.

Lessons Learned & Future Work

- The actuator can accomplish the demanding specifications with
  - $\epsilon = 7\,\mathrm{N} \times \mathrm{W}^{-1} \rightarrow$ **low power dissipation**
  - $t_s = .71\,\mathrm{ms}$ for $\delta = 1\,\mu\mathrm{m} \rightarrow$ **high speed**
  - $\Phi \geq 25\,\mathrm{mm} \rightarrow$ **small separations**
- The Comsol results are (statically) verified by
  - two very simple, preliminary prototypes
  - an analytical optimization

Lessons Learned & Future Work

Further pushing the technology boundaries

VRALA, the last chapter of the short but rich history of the AO technology has established many achievements. The encouraging results indicate the near future developments.

Lessons Learned & Future Work

- Complete prototype (provided with a feedback capacitive sensor)
  - possible construction issues
  - closed loop response
  - power dissipation
- Further computations
  - possible alternative control system designs
  - closed loop frequency response
  - refined multiphysics (HT+NS+SM)
    - cooling system design
    - magneto-mechanics as a function of T
  - 3D modeling
    - whole system simulation (mutual effects)
    - effects of tolerances/errors

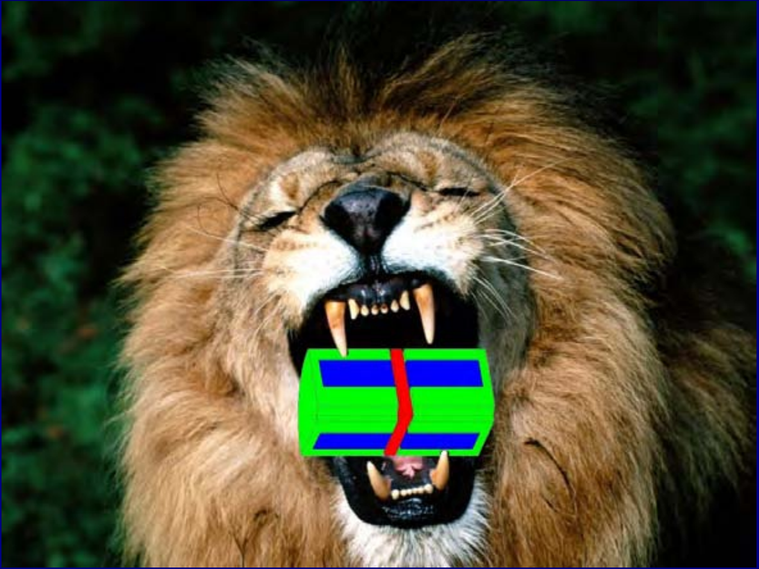
Some Final Explanations

***V**ariable **R**eluctance **A**daptive mirror **L**inear **A**ctuator*

Some Final Explanations

Vråla	To roar
(Swedish)	*(English)*

Some Final Explanations



For Further Reading I

- Del Vecchio, C., Marignetti, F., Agapito, G., Tomassi, G., and Riccardi, A. (2010).
  Vrala: Designing and prototyping a novel, high-efficiency actuator for large adaptive mirrors.
  In Ellerbroek, B. L., Hart, M., Hubin, N., and Wizinowich, P. L., editors, *Adaptive Optics Systems*, volume 7036 of *Proc. SPIE*. SPIE.

For Further Reading II

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.