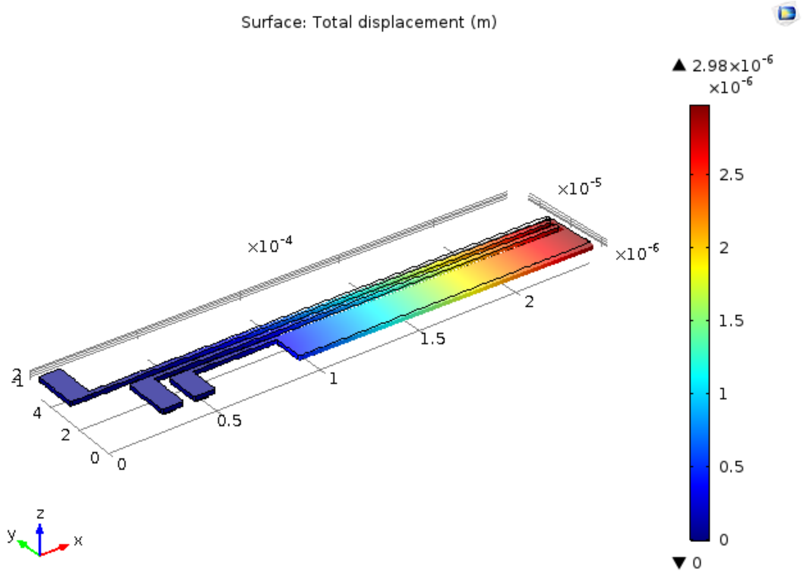
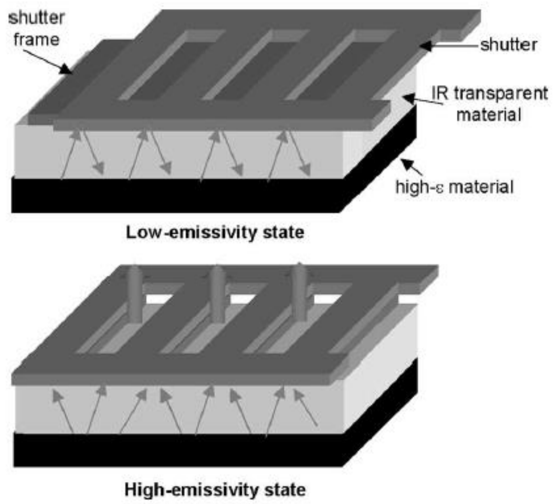
Feasibility Study of Thermal Actuators for MEMS Variable Emittance Radiators Using COMSOL Multiphysics

Lorenzo Pasqualetto Cassinis





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Overview

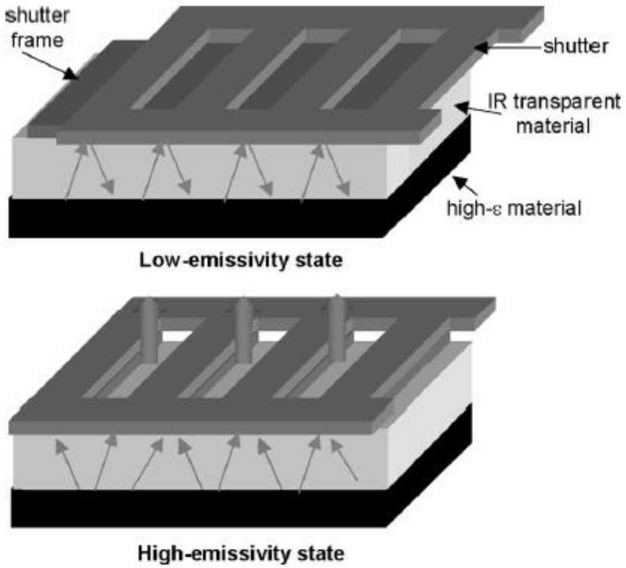
- Introduction
- Motivation of Thermal Actuators
- Model definition in COMSOL Multiphysics
- Governing equations and Boundary Conditions
- Model Validation and Parametric Analysis
- Final Optimization and Conclusions

Introduction

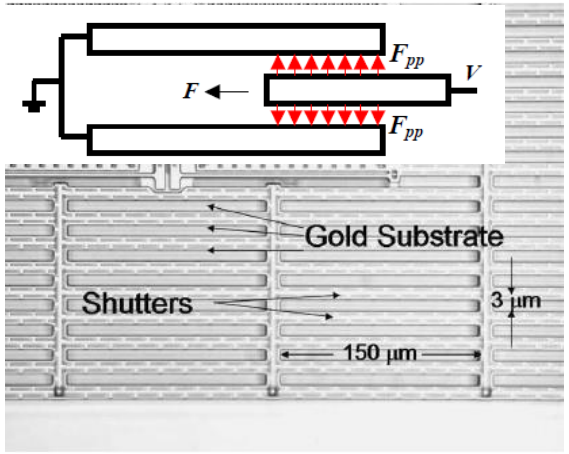
- Variable Emissivity Radiator are devices that vary their emissivity depending on how much heat they have to dissipate. For future CubeSat missions, they are expected to become part of the Thermal Control Subsystem

$$T_R(t) = T_0 + (T_\infty - T_0)[1 - e^{-\frac{k+4A\epsilon\sigma T_0^3}{C_t}t}]$$

- Shutter/Louvres devices have been tested by NASA in ST-5 mission. 1st option is preferred due to compactness (in-plane motion)



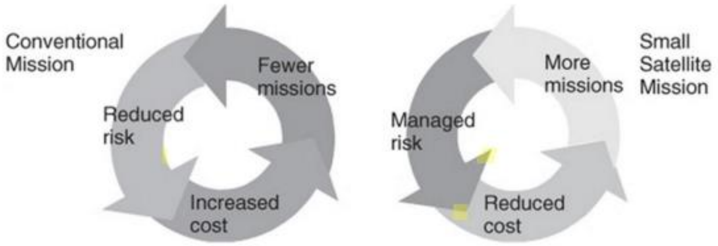
Osiander et al. 2004



Osiander et al. 2004

- State of the art for the actuation system relies on Electrostatic Comb Drives
- High voltages initially required ~100 V. High force-low voltage comb drives voltage is still around 22 V

Motivation of Thermal Actuators



- Trend in mass (and power) decrease – compact devices and low power consumption are required
- CubeSats extending beyond LEO orbits – Radiation harness might be a problem

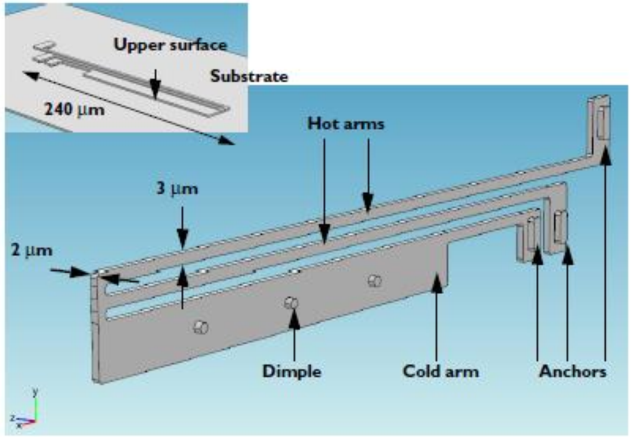
1. Thermal actuators can guarantee relatively high displacement with very low voltage applied, and they are less radiation-sensitive compared to their electrostatic counterpart
2. Lot of research already done in their design and applications, but less work made in their optimization for shutter actuation where 3μm are required

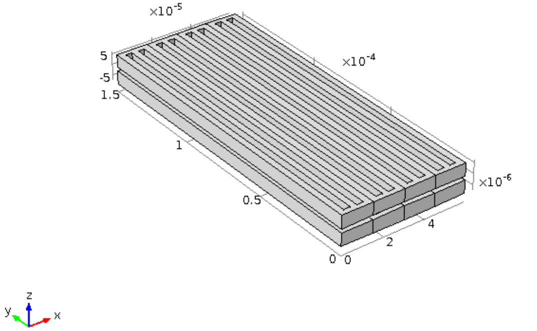
Main goal of the Feasibility Study :

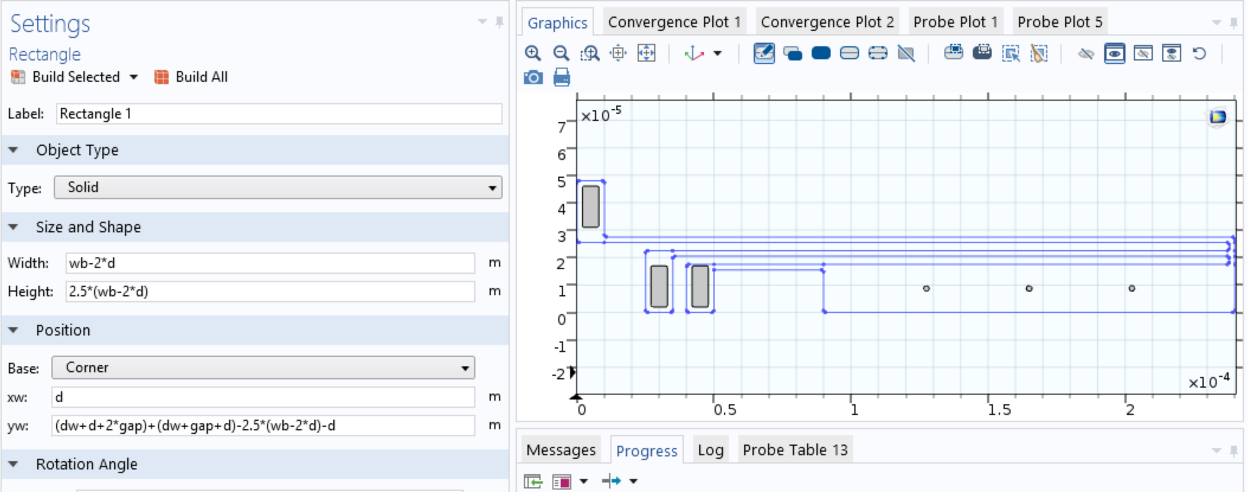
Validate if thermal actuators can provide 3μm displacement of a shutter array with a given stiffness with a reduction in the applied voltage compared to electrostatic comb drives

Model Definition

Name	Value (µm)	Description
d	3	Height of the hot arm
d_w	15	Height of the cold arm
gap	3	Gap between arms
wb	10	Width of the base
wv	50	Length difference between hot arms
L	240	Actuator length
L1	L-wb	Length of longest hot arm
L2	L-wb-wv	Length of shortest hot arm
L3	L-2wb-wv-L/48-L/6	Length of cold arm, thick part
L4	L/6	Length of cold arm, thin part







Settings

Rectangle

Build Selected ▾ Build All

Label: Rectangle 1

▾ Object Type

Type: Solid

▾ Size and Shape

Width: wb-2*d m

Height: 2.5*(wb-2*d) m

▾ Position

Base: Corner

xw: d m

yw: (dw+d+2*gap)+(dw+gap+d)-2.5*(wb-2*d)-d m

▾ Rotation Angle

Governing Equations and Boundary Conditions

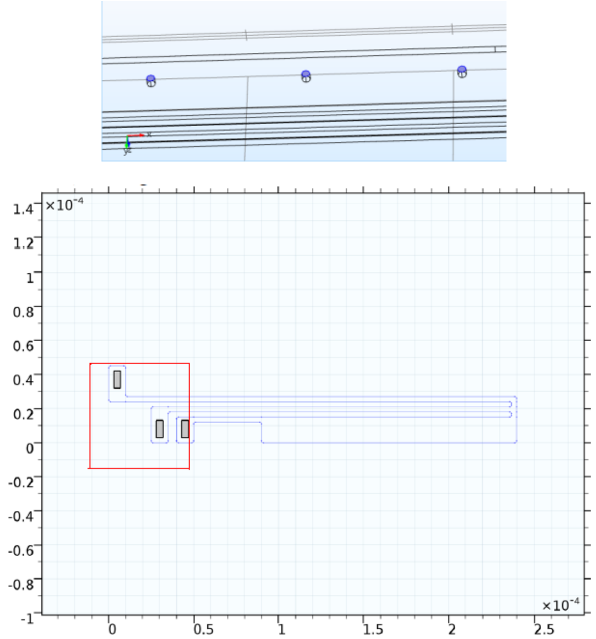


Fig. 1: Zoom on the part of the device where Voltage is applied and dimples where rollers are applied

Boundary Conditions and Assumptions

1. Boundary Temperature Condition: dimples and fixed rectangles (where Voltage is applied) are kept at Spacecraft Temperature T_0
2. Boundary Mechanical Condition: 3 rollers constraint the motion in the +Z direction
3. <u>Radiative Heat Transfer neglected</u>
4. <u>No convection</u>
5. <u>Linear Geometries</u>

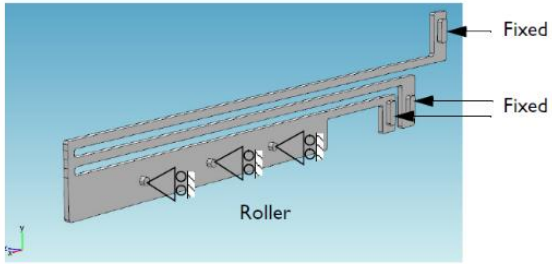
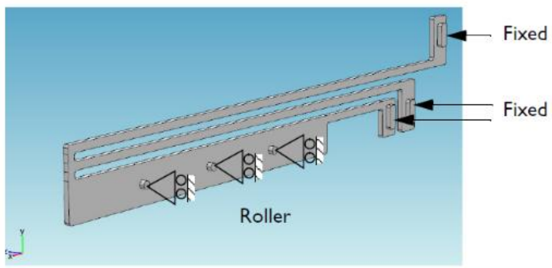


Fig. 2: Mechanical boundary conditions

- Since the material properties of polysilicon are temperature dependent, the involved physics phenomena described above are *fully coupled*. The electric current through the hot arms, generated by the applied Voltage, increases the temperature in the actuator, which in turn causes thermal expansion and changes the electrical conductivity of the material as the resistance $R = \rho \frac{l}{S}$ of the hot and cold arms differs.

Governing Equations and Boundary Conditions



1. The current distribution in the structure for specified voltage boundary conditions is determined by solving the following equation for continuity of current:

$$\nabla \cdot \mathbf{J} + \boldsymbol{i_v} = 0$$

2. After obtaining the current distribution, non-uniform Joule heating is computed as $\dot{q} = \rho|\mathbf{J}|^2$. Then, the following steady-state heat conduction equation is solved for temperature distribution for specified thermal boundary conditions on temperature and heat flux (including insulation and radiation):

$$k\nabla^2 T + \dot{q} = 0$$

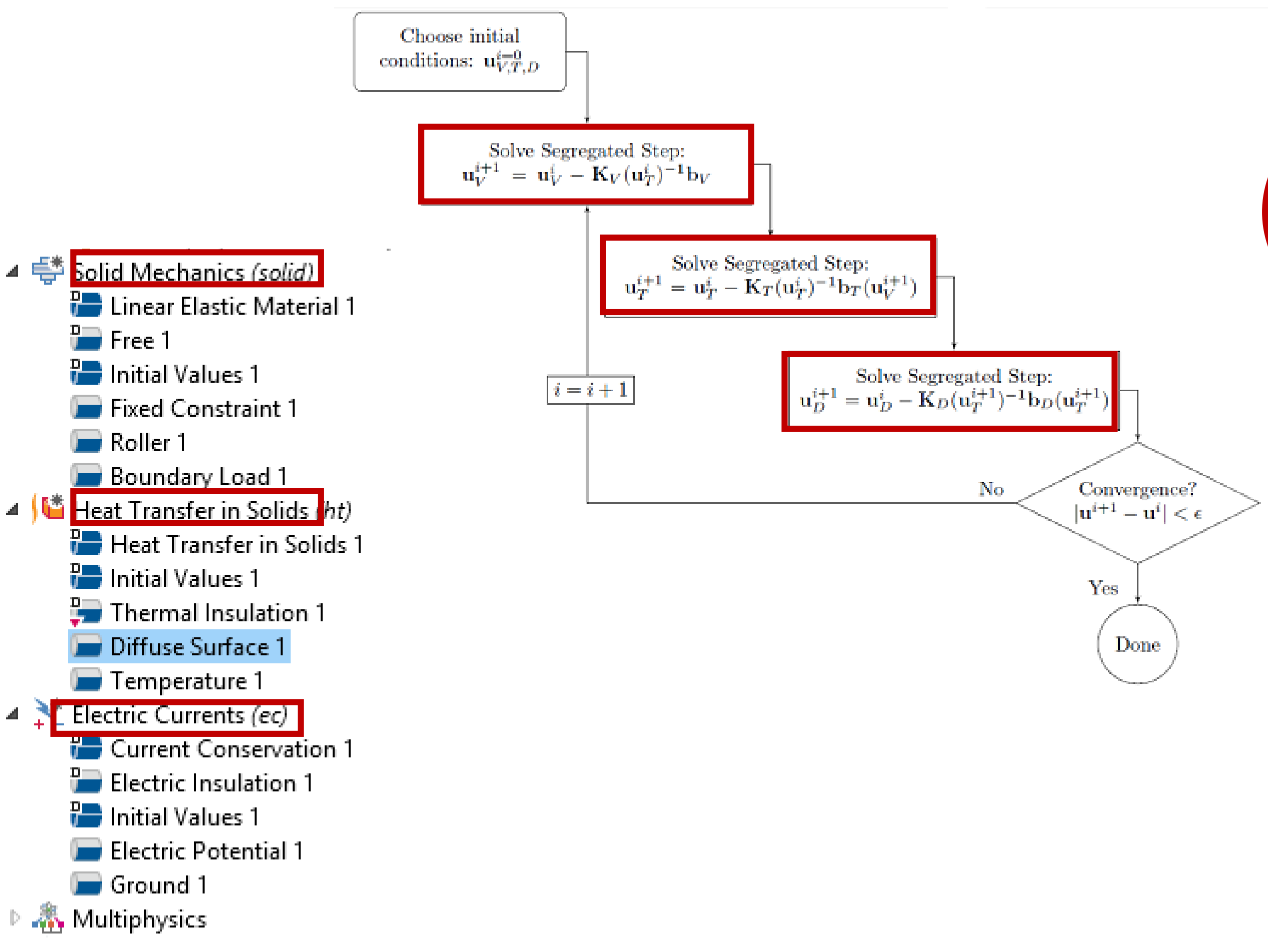
3. The third and final step in the simulation is to solve the elastic equilibrium equations under temperature induced thermal strain:

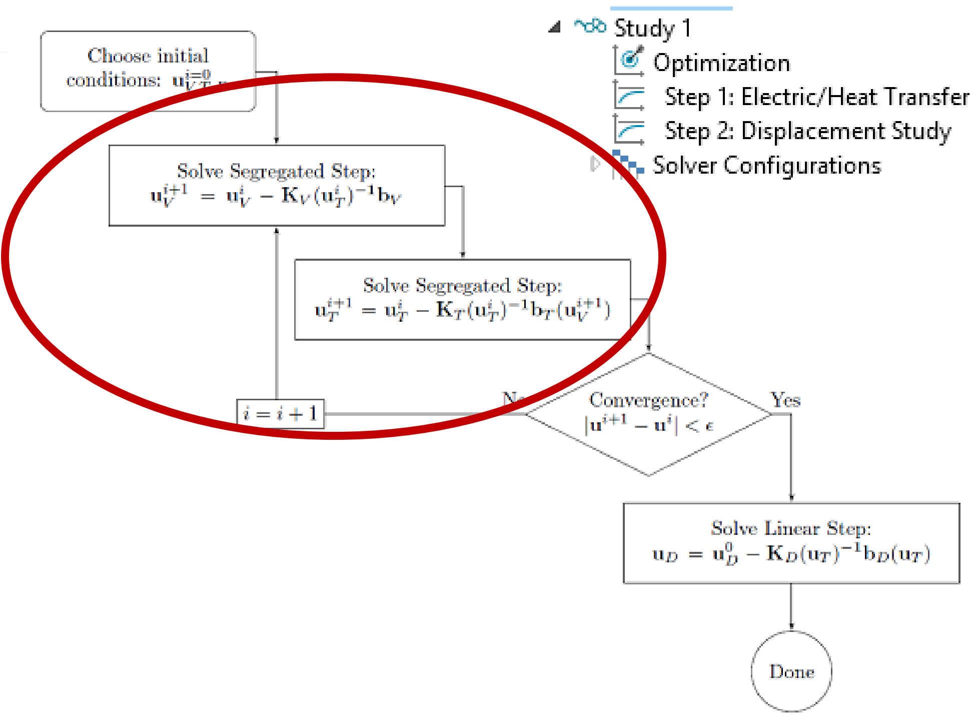
$$\nabla \boldsymbol{\sigma} = 0$$

Property	Symbol	Value	Unit
Coefficient of Thermal Expansion	α	2.6	1/K
Heat Capacity at constant pressure	c_p	678	J/(Kg K)
Relative Permittivity	ϵ_r	4.5	-
Density	ρ	2320	Kg/m^3
Thermal Conductivity	k	34	W/(mK)
Electrical Conductivity	σ	50	kS/m
Young's Modulus	E	160	GPa
Poisson's Ratio	ν	0.22	-

Governing Equations and Boundary Conditions

COMSOL Multiphysics Segregated Approach





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Model Validation & Parametric Study

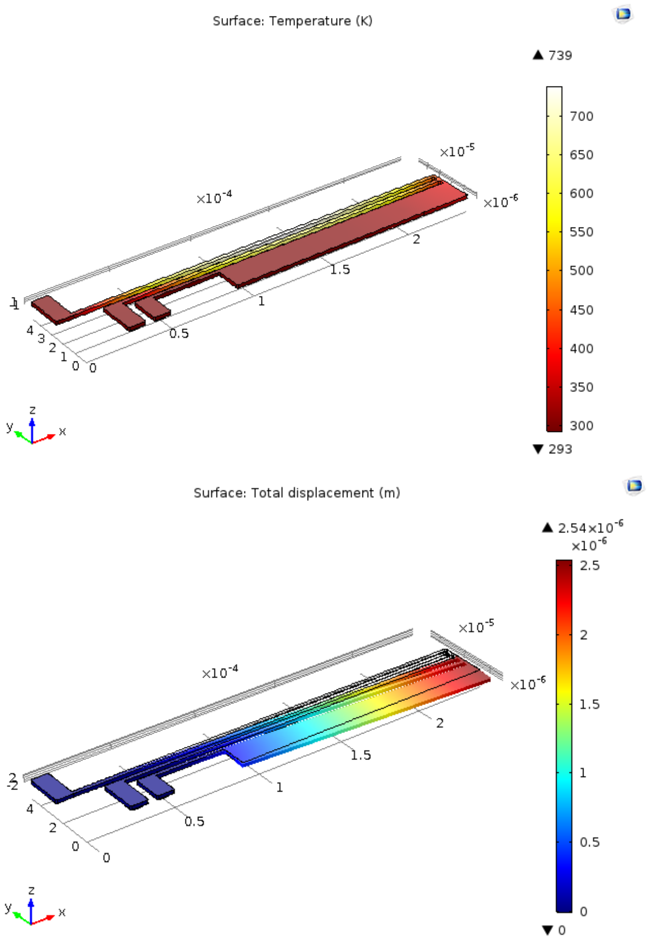


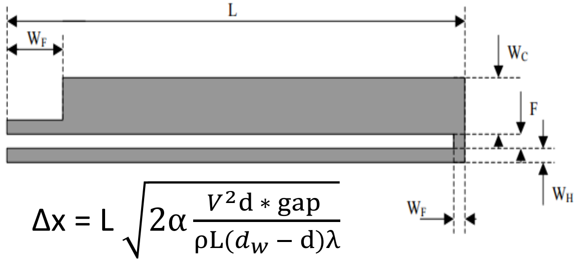
Fig. 1: Displacement and Temperature distribution over the Thermal Actuator – Simple Analysis

Validation of the model:

- output tip displacement is reasonably close to requirements of 3μm (Fig. 1)
- Temperature distribution results in Max. T in the middle of the actuator (Fig. 1 & 3)
- Tip displacement close to analytical results

	Voltage (V)	Length (μm)	Tip Displacement (μm)
Analytical Model	2.5	254	2.11
COMSOL Model			2.54

Difference in result mainly related to number of arms



$$\Delta x = L\sqrt{2\alpha\frac{V^2 d * gap}{\rho L(d_w - d)\lambda}}$$

Fig. 2: Analytical displacement analysis

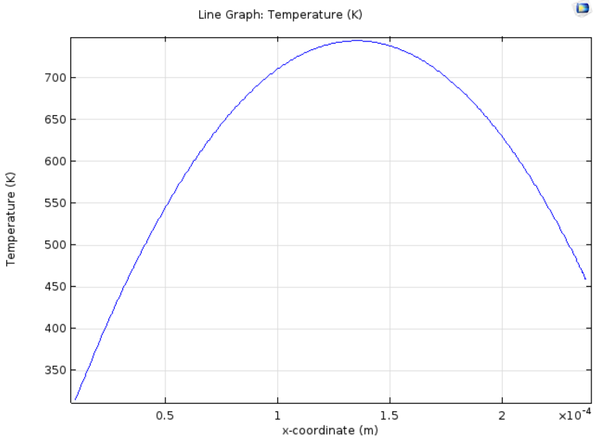


Fig. 3: Temperature distribution over the Thermal Actuator

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Stiffness Calculation

- MEMS gold selected as the material for the shutter array (Fig. 1)
- Roller boundary condition as to avoid unwanted contact between the moving array and the part fixed to the spacecraft, according to the real device
- 1000 N force applied, stiffness obtained from displacement
- Different forces applied to check the linear response (Fig. 2)
- Stiffness k included in the Thermal actuator model

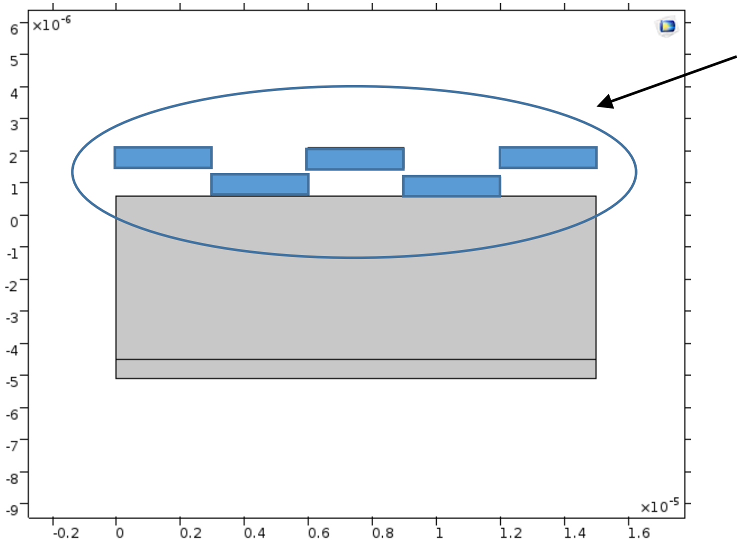
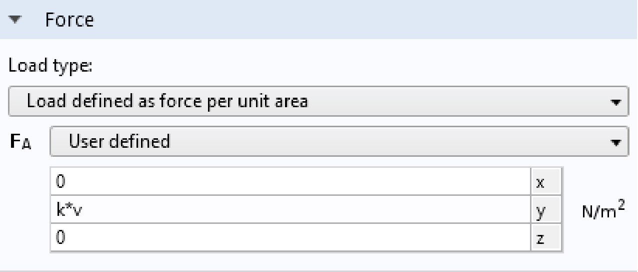

MEMS Gold

Fig. 1: 2D Geometry of the Shutter Array

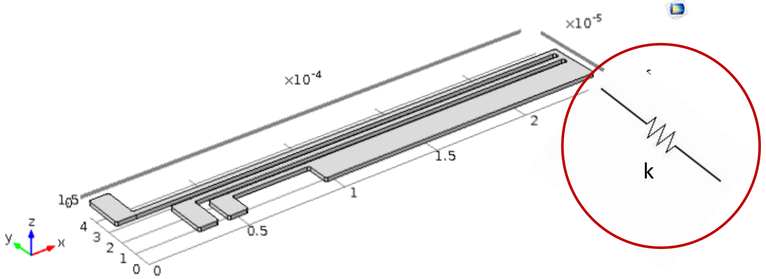

Force

Load type:

Load defined as force per unit area

F_A User defined

0	x	
k*v	y	N/m^2
0	z	



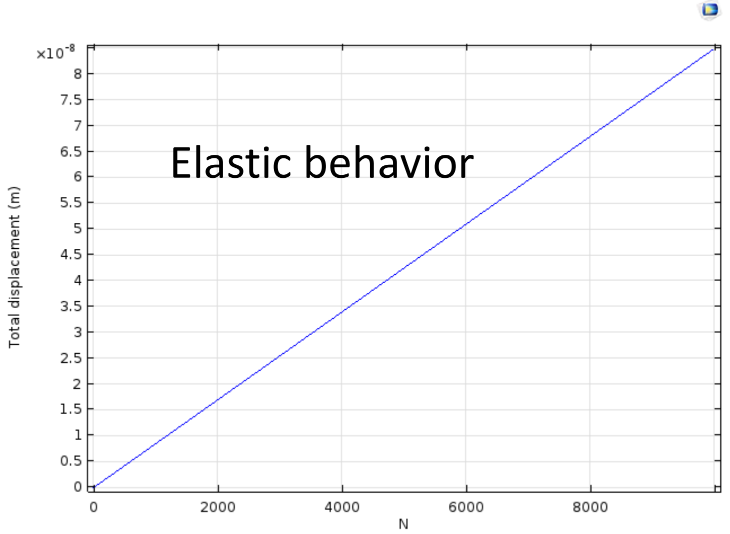

Elastic behavior

Fig. 2: Linear response of the shutter array

Stiffness Calculation (cont'd)

- Considering real dimensions of the device, stiffness is around 10^{11} N/m^3
- Not only high voltages are required to achieve reasonable displacements, but also unwanted displacement, since maximum displacement occurs in the center and not in the tip (Fig.1 & 2)
- 10^9 N/m^3 used as shutter stiffness for Optimization Study

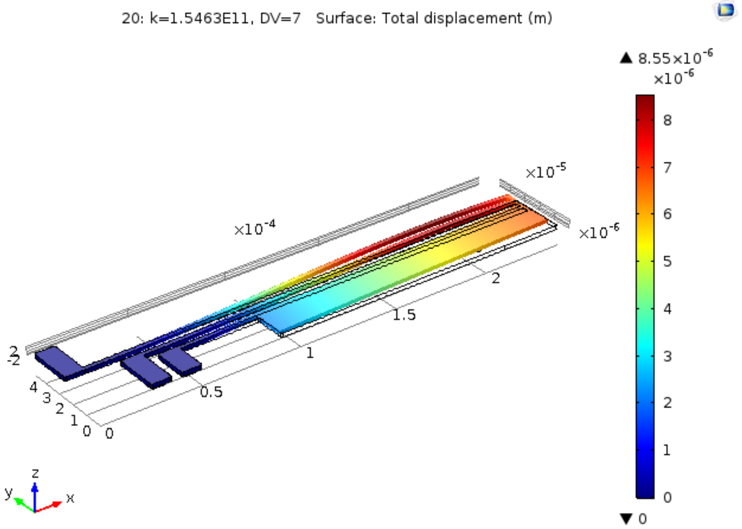


Fig. 1: Displacement distribution when 10^{11} N/m^3 is assumed for the shutter stiffness

k (N/m3)	Voltage (V)	Temperature (K)	Max. Displacement
1.55E+11	4	1250.5	2.67
1.55E+11	5	1720.7	4.02
1.55E+11	6	2197.6	5.45
1.55E+11	7	2639.4	6.83
4.50E+09	3	843.4	4.03
4.50E+09	4	1250.1	7.04

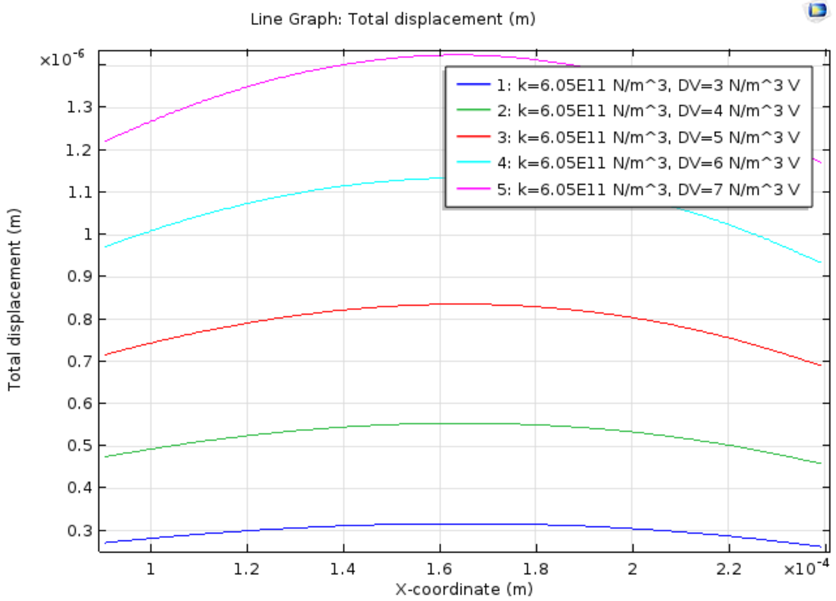


Fig. 2: Displacement distribution. Maximum displacement occurs in the middle of the actuator

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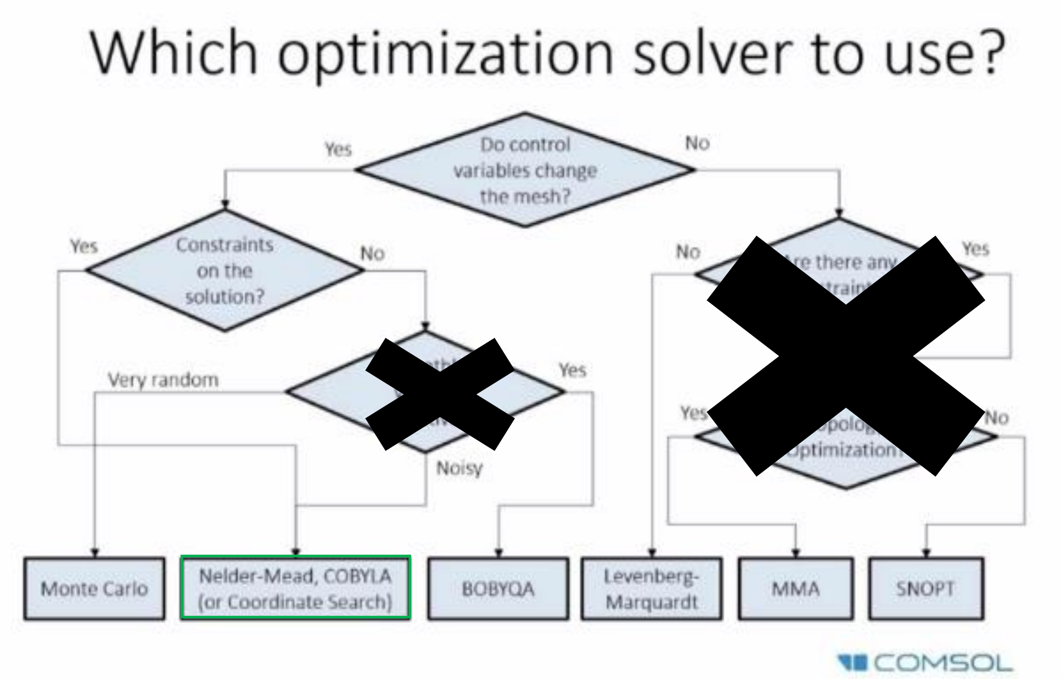
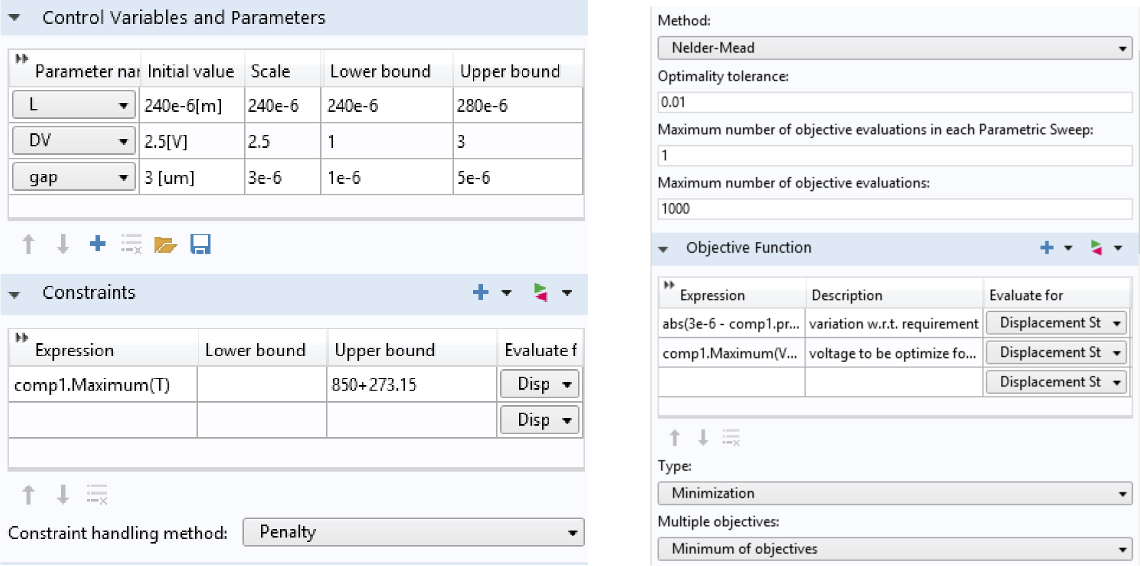
Optimization Study

1. Change in the geometry need to be considered – Remesh required at every Optimisation Step
2. Melting Temperature of PolySilicon shall be considered as a constraint
3. Nelder-Mead selected as Optimization solver





Control Variables and Parameters

Parameter nar	Initial value	Scale	Lower bound	Upper bound
L	240e-6[m]	240e-6	240e-6	280e-6
DV	2.5[V]	2.5	1	3
gap	3 [um]	3e-6	1e-6	5e-6

Constraints

Expression	Lower bound	Upper bound	Evaluate f
comp1.Maximum(T)		850+273.15	Disp
			Disp

Constraint handling method: Penalty

Method: Nelder-Mead

Optimality tolerance: 0.01

Maximum number of objective evaluations in each Parametric Sweep: 1

Maximum number of objective evaluations: 1000

Objective Function

Expression	Description	Evaluate for
abs(3e-6 - comp1.pr...	variation w.r.t. requirement	Displacement St
comp1.Maximum(V...	voltage to be optimize fo...	Displacement St
		Displacement St

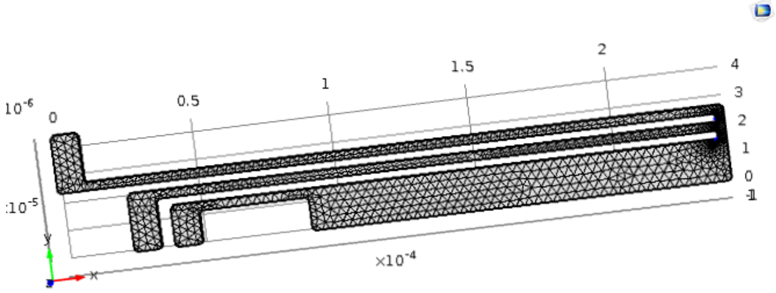
Type: Minimization

Multiple objectives: Minimum of objectives

Fig. 1: 1st and 2nd Optimization Set-up

Challenges in the Optimization:

- Objective functions and Control Variables need to be normalized
- An accurate, fine mesh is required for convergence



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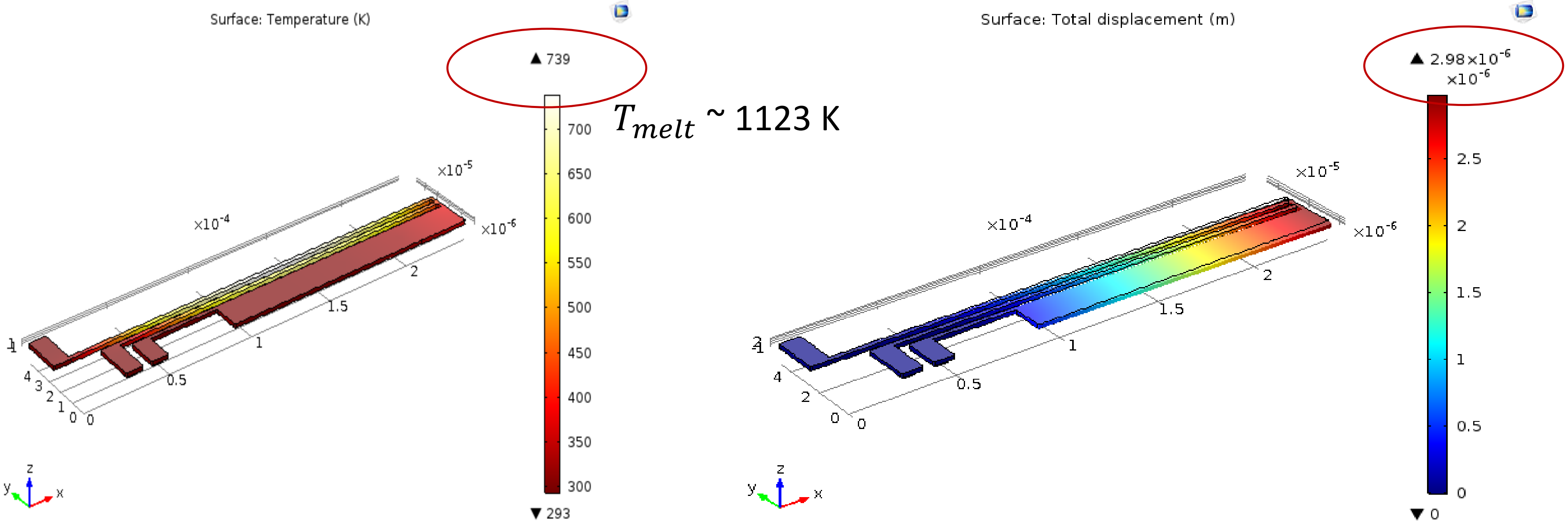
Optimization Study

Results



T_{melt} ~ 1123 K

Fig. 1: Optimization Results – Temperature and Displacement distributions over the Thermal Actuator

Assumptions Validation

- The option **Radiation with participating Media** was considered to check the influence of Radiation on the analysis.
- Updated results are close to scenario without radiation. Reason is MEMS structure is not usually designed for routine operation at powers high enough to generate substantial thermal radiation

- **Non-linear geometry** considered to check if linearities lead to unrealistic results.
- Analysis returned the same results (due to actuator thin thickness), with additional computational time. This validates the assumption of linear geometry

Conclusions

- A single Thermal Actuator can actuate a Shutter Array of stiffness k = 10^9 N/m^3
- Tip displacement results in 2.99/3.01 μm
- Maximum Temperature never exceeds melting point of PolySilicon

	Displacement (μm)	Voltage (V)
Parametric Study	2.54	< 3
1st Optimization	2.98	2.7
Final Optimization	3.01	2.5
Electrostatic Comb Drive	-	22-35

Table 1: Comparison of tip displacements and required voltage for thermal actuators and electrostatic comb drives

Still, there are limitations in the high-level analysis performed!

To be addressed:

- Number of actuators required to actuate the real shutter array (higher stiffness)
- High temperature in the actuator (radiator shall operate at relatively low temperatures)
- Feasibility of thermal actuators for ON/OFF (Fig. 2)

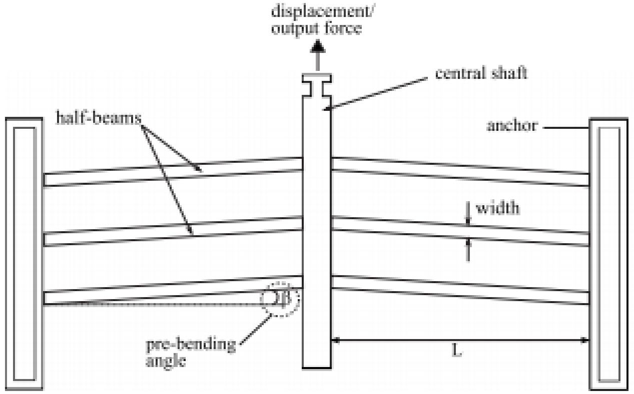


Fig. 1: Schematic drawing of an actuation system comprehensive of more thermal actuators

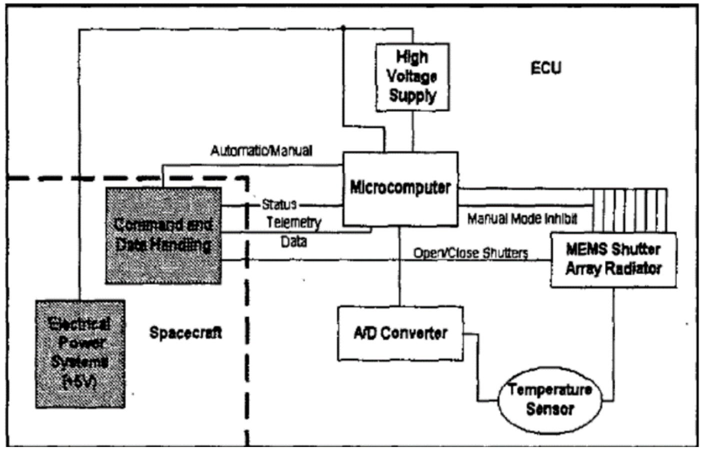


Fig. 2: Mechatronics System comprehensive of shutter array and actuators

Thank you for your attention

Questions?