Modeling and calibration of opto-mechanical chains in additive manufacturing

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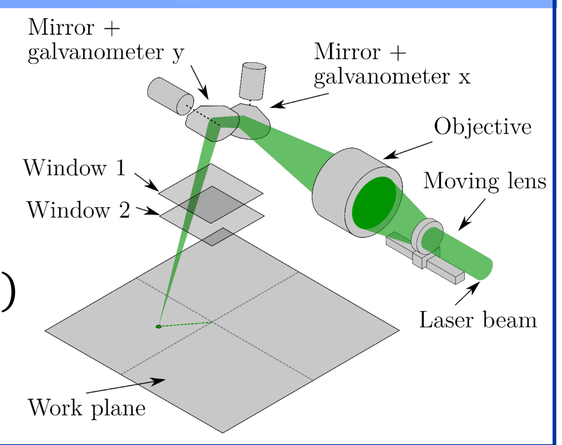
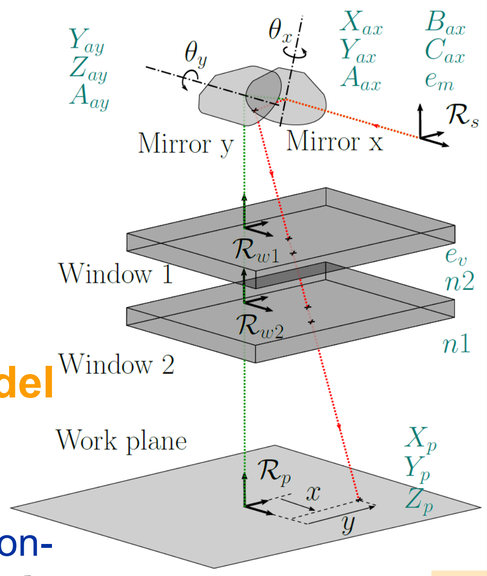
Introduction

- **Issue**
  - The calibration of SLM, SLA and SLS additive manufacturing machines is an iterative process requiring numerous measurements. This machine downtime generates high production costs
- **Objectif**
  - Decrease the calibration time: identify the relationship between the laser spot position $\boldsymbol{X} = (x, y)$ and the mirrors position $\boldsymbol{Q} = (\theta_x, \theta_y)$ by using a virtual machine based model and performing a minimum number of measurement steps



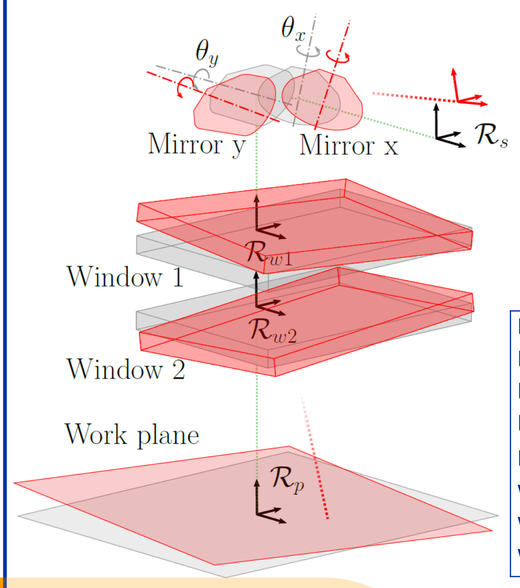
1 - Nominal virtual machine

- **Hypothesis**
  - Orientation and position of components according to the nominal arrangement of the surfaces
  - Geometrical optics
- **Forward kinematic model** $\boldsymbol{X} = h(\boldsymbol{Q})$
  - 13 geometrical parameters
  - 2 optical parameters
- **Inverse kinematic model** $\boldsymbol{Q} = h^{-1}(\boldsymbol{X})$
  - Numerically determined by gradient due to the non-linearities of the function h



2 - Virtual machine with defects

- **Forward kinematic model with defects** $\boldsymbol{X} = f(\boldsymbol{\delta}, \boldsymbol{Q})$
  - Only assembly defects are considered (other defects, optical and thermal, are neglected)

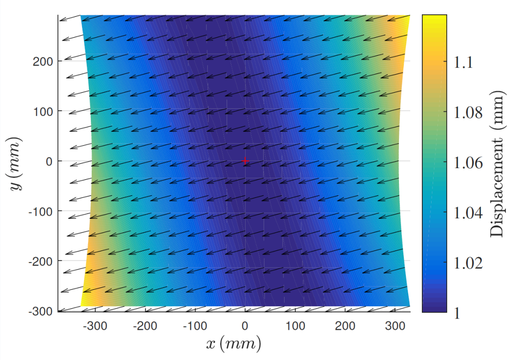


- 30 assembly defects δ_i have an impact on the laser spot position in the work plane

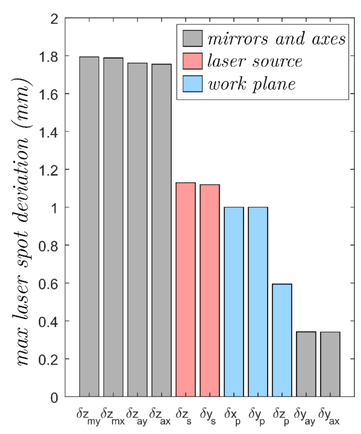
	Position defects			Orientation defects		
	x	y	z	a	b	c
Laser source		δ_{y_s}	δ_{z_s}		δ_{b_s}	δ_{c_s}
Rotary axis x		$\delta_{y_{ax}}$	$\delta_{z_{ax}}$	$\delta_{a_{ax}}$	$\delta_{b_{ax}}$	$\delta_{c_{ax}}$
Mirror x			$\delta_{z_{mx}}$	$\delta_{a_{mx}}$	$\delta_{b_{mx}}$	
Rotary axis y		$\delta_{y_{ay}}$	$\delta_{z_{ay}}$	$\delta_{a_{ay}}$	$\delta_{b_{ay}}$	$\delta_{c_{ay}}$
Mirror y			$\delta_{z_{my}}$	$\delta_{a_{my}}$	$\delta_{b_{my}}$	
Window 1				$\delta_{a_{w1}}$	$\delta_{b_{w1}}$	
Window 2				$\delta_{a_{w2}}$	$\delta_{b_{w2}}$	
Work plane	δ_{x_p}	δ_{y_p}	δ_{z_p}	δ_{a_p}	δ_{b_p}	δ_{c_p}

3 – Defect basis

- Creation of a defect basis from the virtual machine
- **Influence of defects** δ
  - Characterization of each defect influence $I(\boldsymbol{\delta}, \boldsymbol{Q}) = f(\boldsymbol{\delta}, \boldsymbol{Q}) - h(\boldsymbol{Q})$
  - Position and orientation defects of the mirrors have the highest influence on the laser spot position
  - Windows have a negligible impact (1000 times less important than other defects)



Influence of the defect δy_s: deviations between the laser spot positions described by the nominal model and those described by the model with defect



Maximum value of the influence of each position defect on the laser spot position (1 mm defects)

4 - Calibration and validation

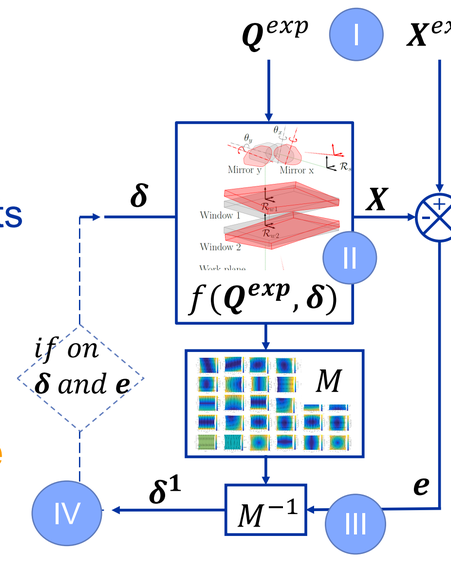
- **Calibration method**

  I - Production of a real data set $(\boldsymbol{Q}^{exp}, \boldsymbol{X}^{exp})$

  II - Use of the virtual machine with defects to simulate the laser spot position $\boldsymbol{X}$

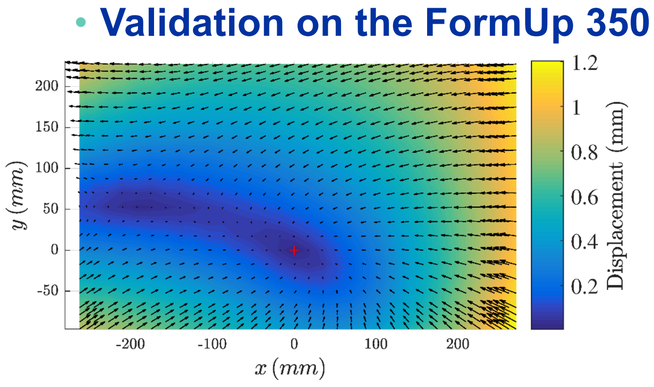
  III - Projection of deviations $\boldsymbol{e}$ between experimental and simulated data on the defects basis

  IV - Identification of a new virtual machine closer to the behavior of the real machine

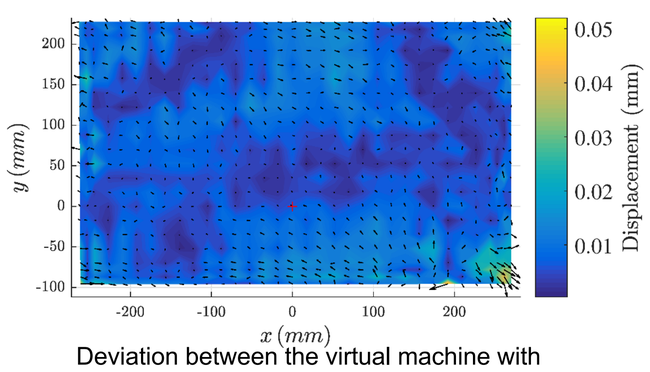


Proposed calibration method

- **Experimentation on industrial machine**
  - **Calibration performed in 1 measurement step and 4 iterations of the algorithm**
  - **95 % of the deviations are less than 20 µm**
  - **Validation on the FormUp 350 machine**



Deviation between the nominal model and the experimental data



Deviation between the virtual machine with identified defects and the experimental data

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