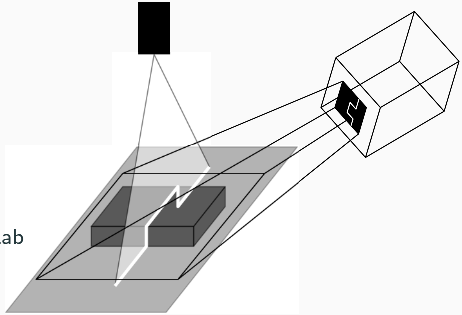
Calibration of laser-triangulation based vision systems under motion

An automated method using rigid sloped artifacts fabricated through additive manufacturing



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Outline

Introduction

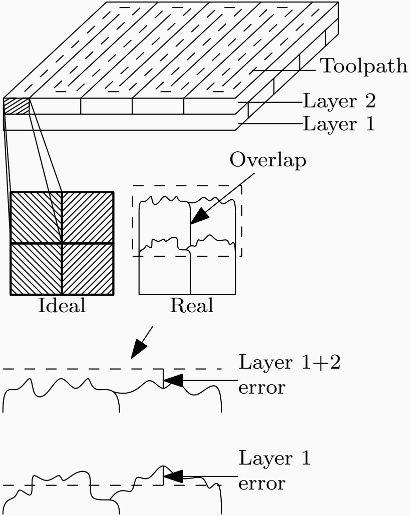
Process control in additive manufacturing

Challenges in AM

- Dimensional accuracy
- Repeatability
- Production time

Solution

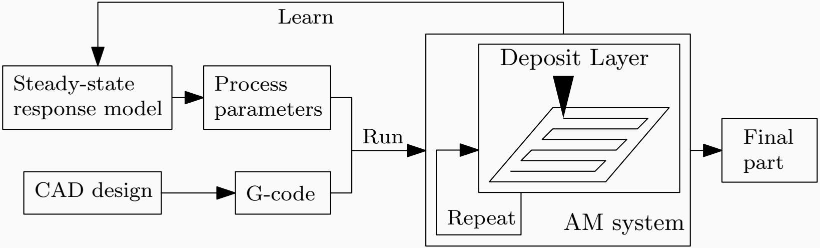
- Deposition geometry control



Process control in additive manufacturing

Deposition control strategies:

- Inter-part feedback control
- Intra-layer feedback control
- Inter-layer feedback control
- **Open-loop control**



Laser triangulation based vision

Solution

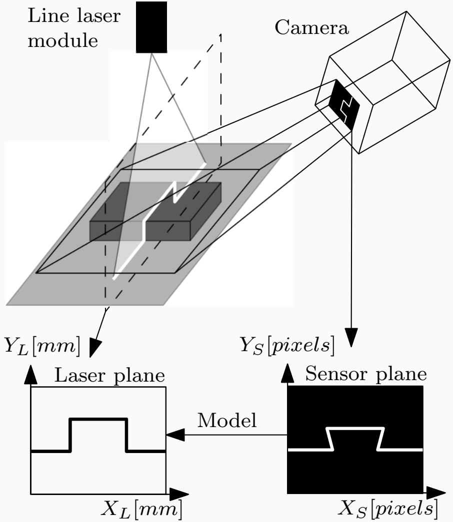
- Laser triangulation

Challenges:

- Perspective view
- Lens distortion
- Line extraction

Required developments

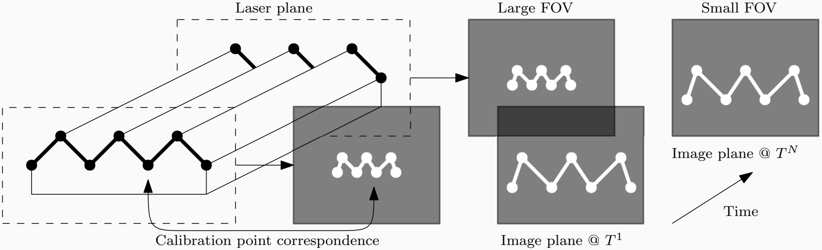
- Projection models
- Calibration method
- Laser line extraction algorithm



Problem statements

Calibration artifact problems

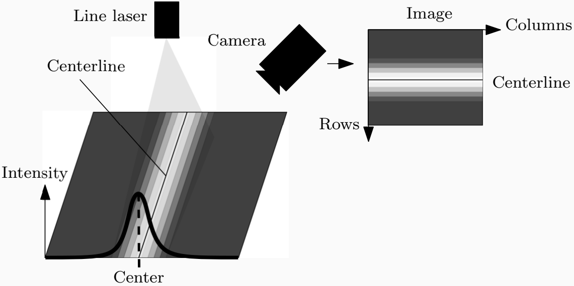
- Flat artifact → lack of point spread → reduced accuracy
- Expensive
- Artifact material not representative of printed material
- Specific artifact needed for each field-of-view (level of zoom)



Problem statements

Line/point extraction problems

- Often algorithms taylored for specific use case
- Use fixed parameters
- Not adaptive to changing reflectivity in material



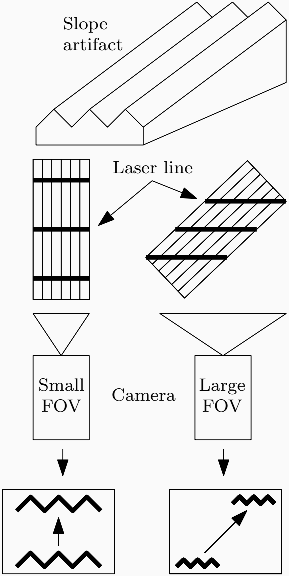
Proposed solutions

Sloped artifact:

- Slope → vertical point spread
- Large FOV → angular orientation for horizontal spread
- Use timing and velocity to determine slope and orientation
- Manufactured by AM machine itself.

Adaptive line/point extraction

- No fixed parameters
- Operate under changing reflectivity, pixel saturation and over/under-filling



Methods

Projection model

Pinhole camera model:

Projection of 3D camera ($\mathbf{x}_c$) to 2D sensor plane ($\mathbf{x}_s$) coordinates

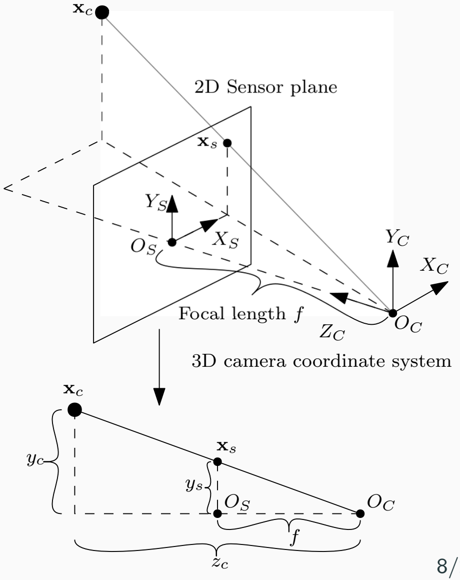
$$\mathbf{x}_s = \begin{pmatrix} x_s \\ y_s \end{pmatrix} = \frac{f}{z_c} \begin{pmatrix} x_c \\ y_c \end{pmatrix} \equiv \begin{pmatrix} f x_c \\ f y_c \\ z_c \end{pmatrix} = \hat{\mathbf{x}}_s$$

In homogenous coordinates:

$$\underbrace{\begin{pmatrix} f x_c \\ f y_c \\ z_c \end{pmatrix}}_{\hat{\mathbf{x}}_s} = \underbrace{\begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}}_{\mathbf{M}_f} \underbrace{\begin{pmatrix} x_c \\ y_c \\ z_c \\ 1 \end{pmatrix}}_{\hat{\mathbf{x}}_c}$$

Combined with operator $\mathcal{H}$:

$$\mathbf{x}_s = \mathcal{H}^{-1}[\,\mathbf{M}_f \cdot \mathcal{H}[\mathbf{x}_c]]$$

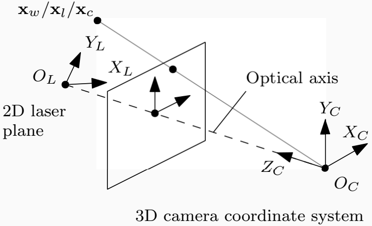


Projection model

Extrinsic view:

2D laser plane ($\mathbf{x}_l$) to 3D camera ($\mathbf{x}_c$) coordinates

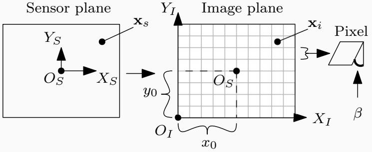
$$\mathbf{x}_c = \mathcal{H}^{-1}\left[\underbrace{\begin{pmatrix} r_1 & r_4 & 0 \\ r_2 & r_5 & 0 \\ r_3 & r_6 & t_z \\ 0 & 0 & 1 \end{pmatrix}}_{\mathbf{M}_e} \mathcal{H}[\mathbf{x}_l]\right]$$



Sensor intrinsics:

2D sensor ($\mathbf{x}_s$) to 2D image ($\mathbf{x}_c$) plane coordinates

$$\mathbf{x}_i = \mathcal{H}^{-1}\left[\underbrace{\begin{pmatrix} s_x & \beta & x_0 \\ 0 & s_y & y_0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathbf{M}_i} \mathcal{H}[\mathbf{x}_s]\right]$$



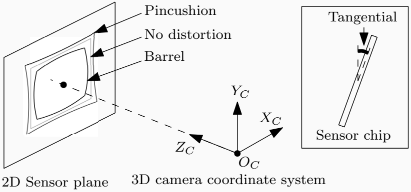
Projection model

Lens distortion compensation:

- Radial distortion ($\mathbf{k}$)
- Tangential distortion ($\mathbf{p}$)

Distorted 2D image ($\mathbf{x}_{di}$) to undistorted 2D image ($\mathbf{x}_i$) coordinates

$$\mathbf{x}_i = \mathbf{D}^{-1}(\mathbf{k}, \mathbf{p}, \mathbf{x}_{di})$$



Projection chain:

2D laser ($\mathbf{x}_l$) to 2D (undistorted) image ($\mathbf{x}_i$) coordinates with $\mathbf{M}_h = \mathbf{M}_i \cdot \mathbf{M}_f \cdot \mathbf{M}_e$.

$$\mathbf{x}_i = \mathcal{H}^{-1}[\,\mathbf{M}_h \cdot \mathcal{H}[\mathbf{x}_l]]$$

Backward projection with lens distortion compensation

$$\mathbf{x}_l = \mathcal{H}^{-1}[\,\mathbf{M}_h^{-1} \cdot \mathcal{H}[\mathbf{D}^{-1}(\mathbf{k}, \mathbf{p}, \mathbf{x}_{di})]\,]$$

Or written as a function of parameters:

$$\mathbf{x}_l = ILP(\mathbf{h}, \mathbf{k}, \mathbf{p}, \mathbf{x}_{di})$$

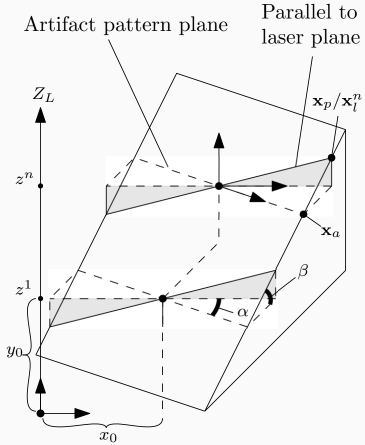
Calibration artifact

Sloped artifact:
2D artifact cross section pattern ($\mathbf{x}_a$) to 2D parallel to laser plane pattern ($\mathbf{x}_p$) coordinates

$$\mathbf{x}_p = \mathcal{H}^{-1}\left[\underbrace{\begin{pmatrix} a & 0 & 0 \\ bc & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathbf{M}_r} \mathcal{H}[\mathbf{x}_a]\right]$$

2D parallel pattern ($\mathbf{x}_a$) to 2D laser plane ($\mathbf{x}_l$) coordinates dependent on image n

$$\mathbf{x}_l^n = \mathcal{H}^{-1}\left[\underbrace{\begin{pmatrix} 1 & 0 & x_0 + c\Delta z^n \\ 0 & 1 & y_0 + ab\Delta z^n \\ 0 & 0 & 1 \end{pmatrix}}_{\mathbf{M}_t^n} \mathcal{H}[\mathbf{x}_p]\right]$$



Laser plane coordinate system

Combined this leads to the

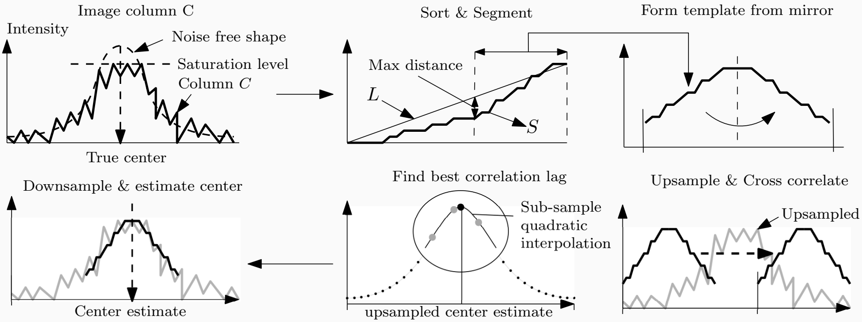
$$\mathbf{x}_l^n = \mathcal{H}^{-1}\left[\mathbf{M}_t^n \mathbf{M}_r \mathcal{H}[\mathbf{x}_a]\right] = ALP(\alpha, \beta, \Delta z^n, \mathbf{x}_0, \mathbf{x}_a)$$

$a = \cos(\alpha)^{-1}, b = \tan(\beta), c = \tan(\alpha), \Delta z^n = V(T^n - T^1)$

Calibration artifact

Column-wise laser centerline extraction:

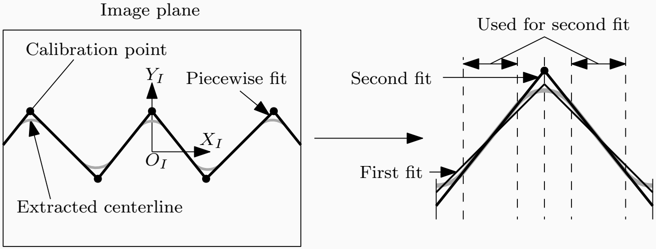
- filtering through sorting → no parameters needed
- laser segmentation from background without differencing
- Saturation does not influence operation
- Every column new template → reflectivity changes allowed
- Relies on symmetry of laser cross section profile



Calibration artifact

Extraction of calibration points:

- Piecewise linear regression
- First fit using all data points → biased through over/under-filling
- Second fit using unbiased sections between points from first fit
- Intersection of coordinates are calibration points in images
- Real relative coordinates in artifact cross section are known.
- Correspondence pairs are used for calibration.



Calibration method

Complete projection model:

$$\mathbf{D}^{-1}(\mathbf{k}, \mathbf{p}, \mathbf{x}_{di}^{n}) = \mathcal{H}^{-1}[\mathbf{M}_h \cdot \mathbf{M}_t^n \cdot \mathbf{M}_r \cdot \mathcal{H}[\mathbf{x}_a]]$$

Training data:

- N images at constant velocity V time-stamped with time $(T^1, T^2, \ldots, T^N)$.
- K known calibration points $(\mathbf{x}_a^1, \mathbf{x}_a^2, \ldots, \mathbf{x}_a^K)$ in artifact cross section pattern
- $K \cdot N$ corresponding points estimated (using line & point extraction algorithms) in all N images $(\mathbf{x}_{di}^{11}, \mathbf{x}_{di}^{12}, \ldots, \mathbf{x}_{di}^{NK})$

Initialisation::
Assumed no lens distortion and no artifact rotation $(\mathbf{M}_r = \mathbf{I})$ such that:

$$\mathbf{x}_i^{nk} = \mathbf{x}_{di}^{nk}, \quad \mathbf{x}_p^k = \mathbf{x}_a^k \quad \forall (n,k) \in S_1$$

where $S_1 = \{(n,k) \in \mathbb{Z}^+ \times \mathbb{Z}^+ | n \leq N \wedge k \leq K\}$

Calibration method

Multi-image direct linear transform:

Perspective projection (homography) where last column is dependent on image n

$$\mathbf{x}_i^{nk} = \mathcal{H}^{-1}[\mathbf{M}_h \mathbf{M}_t^n \mathcal{H}[\mathbf{x}_p^k]] = \mathcal{H}^{-1}\left[\begin{pmatrix} h_1 & h_4 & h_7^n \\ h_2 & h_5 & h_8^n \\ h_3 & h_6 & h_9^n \end{pmatrix} \mathcal{H}[\mathbf{x}_p^k]\right] \quad \forall \quad (n,k) \in S_1$$

Is rewritten as two non-linear equations, linear in parameters

$$x_i^{nk} = \frac{h_1 x_p^k + h_4 y_p^k + h_7^n}{h_3 x_p^k + h_6 y_p^k + h_9^n}, \quad y_i^{nk} = \frac{h_2 x_p^k + h_5 y_p^k + h_8^n}{h_3 x_p^k + h_6 y_p^k + h_9^n} \quad \forall (n,k) \in S_1$$

Combining all equations leads to the following set of homogenous linear equations:

$$\mathbf{Ah} = \mathbf{0}$$

SVD $\rightarrow$ minimizes $||\mathbf{Ah}||^2$ which is an algebraic error $\rightarrow$ not geometrical meaningfull.

Calibration method

Artifact slope and orientation estimation: Estimated image dependent parameters are defined as:

$$h_7^n = h_1(x_0 + c\Delta z^n) + h_4(y_0 + ab\Delta z^n)$$
$$h_8^n = h_2(x_0 + c\Delta z^n) + h_5(y_0 + ab\Delta z^n)$$
$$h_9^n = h_3(x_0 + c\Delta z^n) + h_6(y_0 + ab\Delta z^n) + h_9$$

which can be rewritten as a system (for all images) of linear equations as:

$$\mathbf{Lb} = \mathbf{k}$$

which is solved using the SVD resulting in estimated parameters $\mathbf{b} = (h_9, x_0, y_0, x_1, y_1)$ and

$$x_1 = c = \tan(\alpha)$$
$$y_1 = ab = \cos(\alpha)^{-1}\tan(\beta)$$

An estimate for artifact rotation angle α can now be determined by:

$$\alpha = \tan^{-1}(x_1)$$

which can be used to estimate the artifact slope angle β as:

$$\beta = \tan^{-1}(y_1 \cos(\alpha))$$

Calibration method

Iterative linear parameter optimization:
Use estimated angles α and β to update all $\mathbf{x}_p$. Then loop and break if converged.

$$\mathbf{x}_p^k = \mathcal{H}\Bigg[\underbrace{\begin{pmatrix} \cos(\alpha)^{-1} & 0 & 0 \\ \tan(\beta)\tan(\alpha) & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathbf{M}_r} \mathcal{H}[\mathbf{x}_a^k]\Bigg] \quad \forall k \in S_3$$

Lens distortion
Estimate (undistorted) image points using the estimated parameters

$$\mathbf{x}_i^{nk} = \mathcal{H}^{-1}[\mathbf{M}_h \mathbf{M}_t^n \mathcal{H}[\mathbf{x}_p^k]] \quad \forall (n,k) \in S_1$$

Use (distorted) points $\mathbf{x}_{di}^{nk}$ and (undistorted) points to estimate distortion

Non-linear refinement
Minimize difference $\overleftarrow{\mathbf{x}}_l^{nk} = ILP(\mathbf{h}, \mathbf{k}, \mathbf{p}, \mathbf{x}_{di}^{nk})$ and $\overrightarrow{\mathbf{x}}_l^{nk} = ALP(\alpha, \beta, \Delta z^n, \mathbf{x}_0, \mathbf{x}_a)$

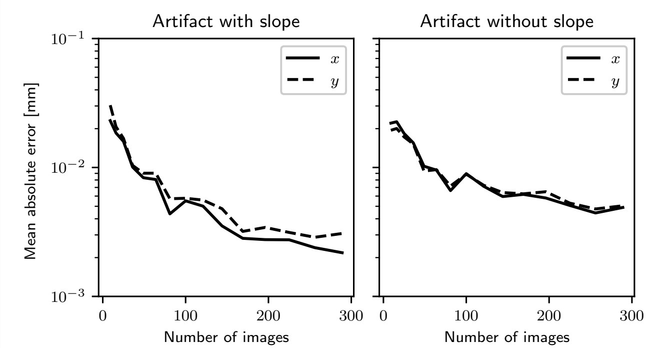
$$E(\mathbf{h}, \mathbf{k}, \mathbf{p}, \alpha, \beta) = \sum_{n=1}^{N} \sum_{k=1}^{K} ||\overrightarrow{\mathbf{x}}_l^{nk} - \overleftarrow{\mathbf{x}}_l^{nk}||^2$$

Results

Simulation

Simulated artifact with and without slope

- larger number of point/images → better estimation
- More spread of points → better estimation
- > 200 images best result → used for experiment



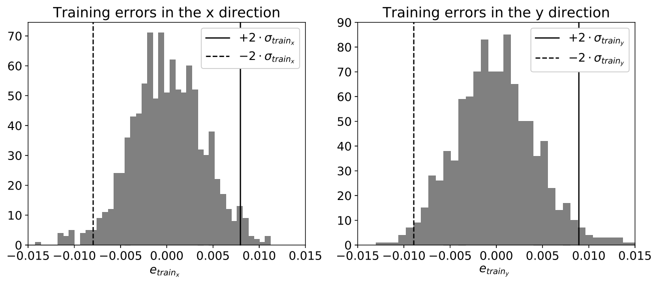
Experiment

Printed sloped artifact errors

Training errors are normally distributed $\rightarrow 95\%$ confidence interval:

$$e_{train_x} = 0.0002 \pm 0.008[mm], \quad e_{train_y} = 0.0001 \pm 0.009[mm]$$

Training errors form upperbound (conservative) on real estimation error.



Conclusions

Conclusions

Conclusions:

- Fully automated calibration $\rightarrow$ no human interaction
- Sloped artifact $\rightarrow$ improved calibration accuracy
- Calibrates with unknown slope and orientation
- Robust adaptive line and point extraction algorithms
- Iterative method for linear parameter estimation
- Possible to calibrate on AM printed artifact.

Questions?