Multi-level Random Sample Consensus Method for Improving Structured Light Vision Systems

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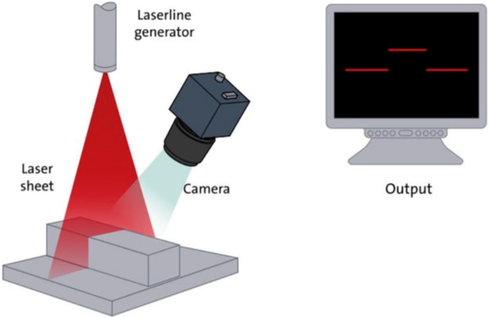
Agenda

- Introduction
- Motivation & Objective
- Theory of multiple shots and multiple laser emitters
- Multi-level RANSAC
- Experiment result and comparison
- Conclusion

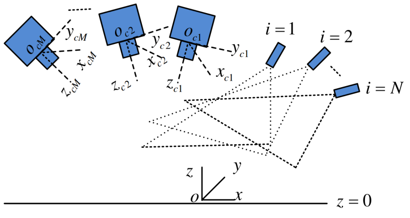
Introduction

- Configuration
  - Laser emitter
    structured light
  - Camera
    capture image
  - Computer
    post process

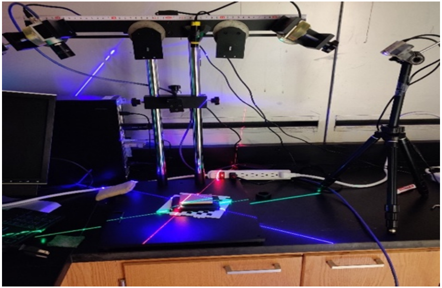


Motivation & Objective

- Motivation
  - Multiple shots, multiple lasers theory
  - Multi-level RANSAC
- Objective
  - Height measurement
  - Tackle the intersection points of the multiple laser planes

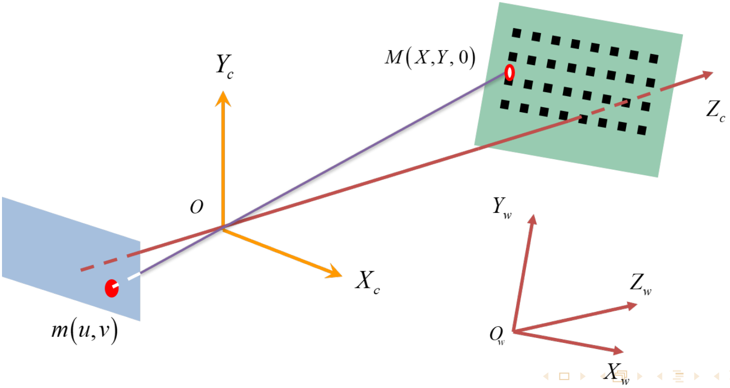


(a) The schematic of multiple shots, lasers



(b) Experiment configuration

- Coordinate system
  - World system
    $M = [X, Y, Z]^T, \tilde{M} = [X, Y, Z, 1]^T$
  - Camera system
    $M_c = [X_c, Y_c, Z_c]^T$
  - Pixel system
    $m = [u, v]^T, \tilde{m} = [u, v, 1]^T$



Theory of multiple shots and multiple laser emitters

- step 1: Zhang's camera calibration
  - Basic equation
    $s\ \tilde{m} = A\ [R \quad t]\ \tilde{M}$
  - Known variables
    - pixel coordinates $\tilde{m} = [u, v, 1]^T$
    - world coordinates $\tilde{M} = [X, Y, 0, 1]^T$ on plane $Z = 0$
  - Other variable
    - depth to pinhole $s = Z_c$
  - Calibrated parameters
    - camera intrinsic matrix $A = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix}$
      (u_0, v_0) the coordinates of the principal point
      α, β the scale factors in image u and v axes
      γ the parameter describing the skewness of the two image axes
    - extrinsic matrix $[R \quad t] = \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} & t_1 \\ r_{2,1} & r_{2,2} & r_{2,3} & t_2 \\ r_{3,1} & r_{3,2} & r_{3,3} & t_3 \end{bmatrix}$
      R rotation matrix
      t translation

Theory of multiple shots and multiple laser emitters

- step 2: Laser plane calibration (stage 1)
  - Basic equations
    $s\ \tilde{m} = A\ M_c, \quad \pi_0^T \begin{bmatrix} M_c \\ 1 \end{bmatrix} = 0$
  - Known variables
    - pixel coordinates $\tilde{m} = [u, v, 1]^T$
    - camera intrinsic matrix A
    - checkerboard plane $(Z = 0)$ $\pi_0 = \begin{bmatrix} R & t \\ 0^T & 1 \end{bmatrix}^{-T} \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$

    $$Z = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \tilde{M} = 0 \Longleftrightarrow \pi_0^T \begin{bmatrix} M_c \\ 1 \end{bmatrix} = 0$$
  - Calculated camera coordinates
    - depth to pinhole $s = Z_c$
    - camera coordinates $M_c = [X_c, Y_c, Z_c]^T$ for points on intersection of the checkerboard plane & the laser plane

Theory of multiple shots and multiple laser emitters

- step 2: Laser plane calibration (stage 2)
  - Basic equations
    $\pi^T \begin{bmatrix} M_c \\ 1 \end{bmatrix} = 0$
  - Known variables
    - camera coordinates $M_c = [X_c, Y_c, Z_c]^T$ for points on intersection of the checkerboard plane & the laser plane
  - Method
    - convert M_c for multiple camera systems into the same camera system
    - estimate π with the least-squares method
  - Calibrated parameters
    - laser plane $\pi = [a, b, c, -1]^T$

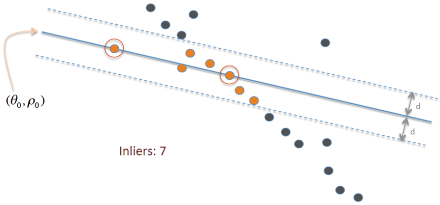
Theory of multiple shots and multiple laser emitters

- step 3: Height measurement
  - Basic equations

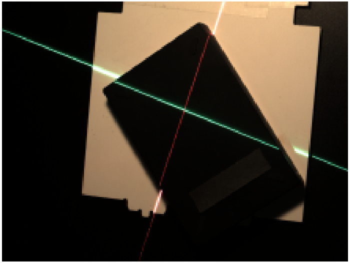
    $$s\ \tilde{m}' = A\ M'_c, \quad \pi^T \begin{bmatrix} M'_c \\ 1 \end{bmatrix} = 0, \quad M'_c = [R \quad t]\ \tilde{M}' = RM' + t$$
  - Known variables
    - pixel coordinates $\tilde{m}' = [u', v', 1]^T$ for points on intersection of the object surface & the laser plane
    - laser plane $\pi = [a, b, c, -1]^T$
    - camera intrinsic matrix A
    - extrinsic matrix $[R \quad t]$
  - Calculated coordinates
    - camera coordinates $M'_c = [X'_c, Y'_c, Z'_c]^T$ for points on intersection of the object surface & the laser plane
    - world coordinates $M' = [X', Y', Z']^T$ for points on intersection of the object surface & the laser plane
    - "Height" $H = \frac{1}{N} \sum Z'$ average for all the points on intersection of the object surface & the laser plane

Multi-level RANSAC

- Multi-level RANSAC
  - Objective
    Tackle the intersection points of the multiple laser planes
  - RANSAC
    - random sample consensus
    - usage: robust fitting in the presence of many data outliers
    - straight line $\omega^T \tilde{m} = \omega^T [u, v, 1]^T = 0$, where $\omega = [\lambda_1, \lambda_2, \lambda_0]^T, \lambda_1^2 + \lambda_2^2 = 1$
    - inlier: $|\omega^T \tilde{m}| \leq d$, outlier: $|\omega^T \tilde{m}| > d$



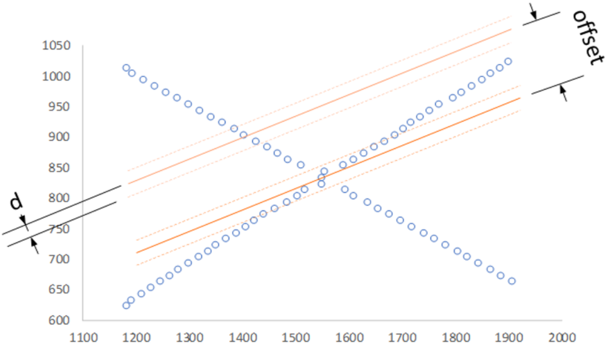
(a) RANSAC algorithm



(b) Captured image of two lasers

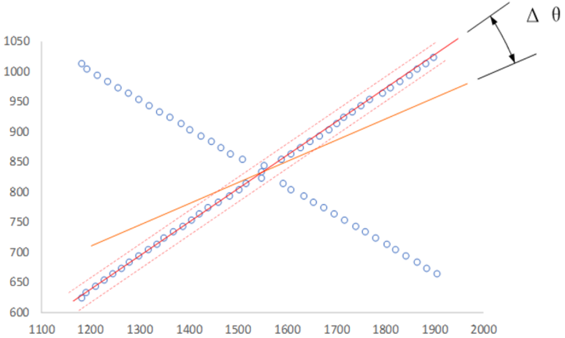
Multi-level RANSAC

- Multi-level RANSAC
  - Level 1
    - initialize $\omega_0 = [\lambda_{10}, \lambda_{20}, \lambda_{30}]^T$ with the least-squares method for points on intersection of horizontally placed checkerboard & the laser plane
    - fix the slope of line $[\lambda_1, \lambda_2] = [\lambda_{10}, \lambda_{20}]$
    - find best offset λ_0, to maximize the number of inliers $|\omega^T \tilde{m}| = \left|[\lambda_{10}, \lambda_{20}, \lambda_0]^T \tilde{m}\right| \leq d$



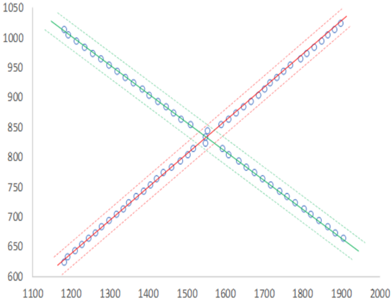
Multi-level RANSAC

- Multi-level RANSAC
  - Level 2
    - randomly choose two points $p_1 = (u_1, v_1), p_2 = (u_2, v_2)$ for K times to make a new line $\omega' = [\lambda'_1, \lambda'_2, \lambda'_0]^T$
    - ensure the angle $\cos(\Delta\theta) = |\vec{n}^T \vec{n}_0| > th$ btw. the new line & initial line where the normal vectors $\vec{n} = [\lambda'_1, \lambda'_2]^T, \vec{n}_0 = [\lambda_{10}, \lambda_{20}]^T$
    - update $\omega \leftarrow \omega'$
      if the number of inliers $|\omega'^T \tilde{m}| \leq d$ is greater than that of ω

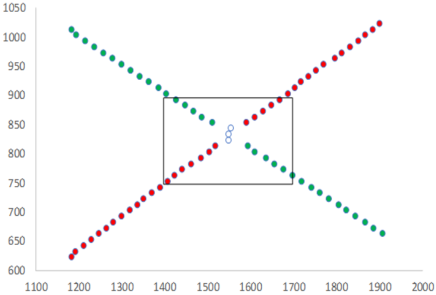


Multi-level RANSAC

- Multi-level RANSAC
  - "best straight line"
    - suppose there are N lasers, each laser has "best straight line" $\omega_i,\ \ i = 1 \cdots N$
    - point $p = (u, v), \tilde{m} = [u, v.1]^T$ is inlier of i-th laser ω_i if $|\omega_i^T \tilde{m}| \leq d$ and $|\omega_j^T \tilde{m}| > d$ for all $j \neq i$
    - some points are not inlier of any ω_i

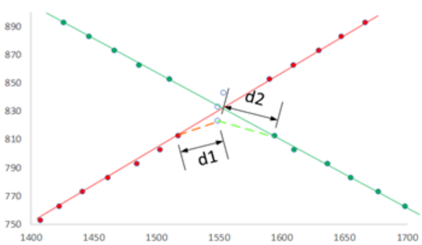


(a) The "best straight line"

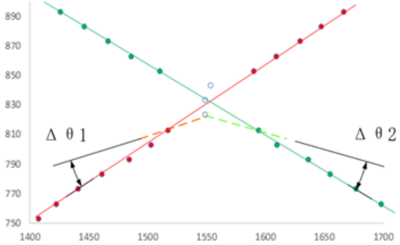


(b) Some points that cannot be decided

- Multi-level RANSAC
  - Level 3
    - for point $p = (u, v)$ that cannot be decided
    - distance factor
      $i = \operatorname{argmin}_i d_i$, where d_i is the shortest distance from p to inliers of ω_i
      if $|d_j / d_i| > th$ for all $j \neq i$, then p is inlier of i-th laser ω_i
    - direction factor
      $i = \operatorname{argmin}_i \Delta\theta_i = \operatorname{argmax}_i \cos(\Delta\theta_i)$, where $\Delta\theta_i$ is the angle formed from the line segment of p and the nearest inlier of ω_i & laser ω_i itself



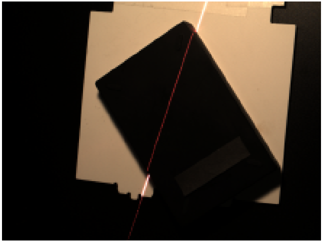
(a) The distance factor



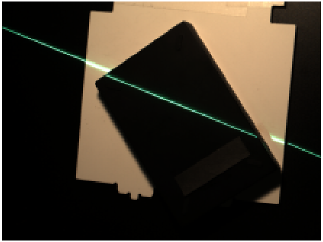
(b) The direction factor

Experiment result and comparison

- Methods
  - Multi-level RANSAC
    - single shots, multiple lasers
    - multiple shots, multiple lasers
  - Time division
    operate laser emitters sequentially
  - Color division
    operate laser emitters concurrently
    distinguish laser plane with color:
    Red laser $250 \leq R; G, B \leq 170$ Green laser $230 \leq G; R, B \leq 220$



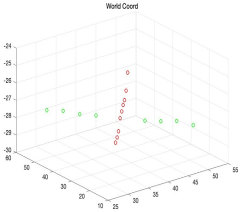
(a) Red laser



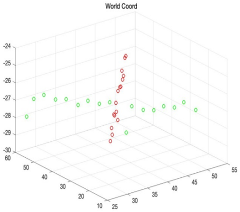
(b) Green laser

Experiment result and comparison

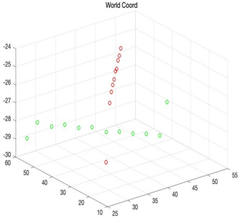
- Experiment result
  - Multi-level RANSAC
  - Time division
  - Color division



(a) Multi-level RANSAC



(b) Time division



(c) Color division

Experiment result and comparison

- Comparison

Table: **Relative errors** of time division, color division and multi-level RANSAC

No.	Time division	Color division	MLRANSAC single camera	MLRANSAC two cameras
1	3.01%	6.92%	**1.30%**	**2.08%**
2	**-2.01%**	3.90%	-7.41%	-3.23%
3	-2.92%	**1.20%**	-10.13%	-6.85%
4	4.20%	8.29%	4.87%	**3.61%**
5	-3.82%	6.34%	-7.43%	**-3.34%**
6	-5.96%	3.80%	-9.40%	**-5.19%**

Conclusion

- Conclusion
  - Framework for multiple shots and multiple laser emitters are developed
  - Multi-level RANSAC algorithm is further developed using the computer vision techniques to compare with time division and color division approaches

	Time division	**Color division**	**MLRANSAC**
Simple operation	✗	✓	✓
Simple process	✓	✓	✓
Luminance effect	✓	✗	✓
Accurate	✗	✓	✓

  - The experiments demonstrate that the system with multiple cameras and multiple laser emitters using the multi-level RANSAC (MLRANSAC) algorithm improves the accuracy of height measurement over the single camera