Efficient range estimation and material quantification from multispectral Lidar waveforms

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Ranging using multispectral Lidar (MSL)

Principle

- Pulsed laser (20 MHz), low power ($\approx \mu$W)
- Detector: single-photon avalanche diode (SPAD)
- Time of flight: for each detected photon (precision $\approx 10^{-12}$s)
Motivations

- Joint extraction of geometric and spectral information
  - Limited data registration issues (fusion Lidar/HSIs)
- Range estimation: robustness
  - Energy spread across wavelengths
- Scene reconstruction with few photons
  - < 10 useful photons per pixel and band
- Robustness: illumination conditions (active imaging)
  - Shadowing effects
Observation model

\[ y_{n,\ell,t} \sim \mathcal{P} (r_{n,\ell} g_{0,\ell} (t - t_n) + b_{n,\ell}) \quad t \in \{1, \ldots, T\} \]

- \( y_{n,\ell,t} \): photon count in the \( t \)th bin (\( \ell \)th band)
- \( r_{n,\ell} \): target reflectivity
- \( t_n \): ToF
- \( g_{0,\ell} (\cdot) \): instrumental response
- \( b_{n,\ell} \): background level

Single target model

- Estimation of \( t_n \), \( r_n = \{r_{n,\ell}\} \) (and \( b_{n,\ell} \))
- Here \( b_{n,\ell} << r_{n,\ell} \)
Efficient range estimation and material quantification from MSL data

Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Clustering/Classification

RGB image (5 × 5 cm)  Range profile (mm)  Spectral classification

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Multispectral Lidar: spectral unmixing

Single-photon Multispectral Lidar

Proposed Bayesian approach

\[ r_n = Ma_n \]

- **M**: known endmember matrix
- **\( a_n \)**: \( n \)th abundance vector
- Observation model: joint likelihood (Poisson noise)
- Standard priors for the unknown parameters
  - smooth abundance maps + sparse mixtures: Total-variation (TV) and \( \ell_1 \) regularizations
  - No abundance sum-to-one constraint
  - Uniform prior for \( t_n \) (regular grid)
- Estimation of \( A = \{a_n\} \) and \( T = \{t_n\} \)
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Single-photon Multispectral Lidar

Previous method

- $f(A, T|Y) \propto f(Y|A, T)f(A, T)$: highly multimodal
  - MCMC method to exploit $f(A, T|Y)$
  - Measures of uncertainty but high computational cost

Proposed method

$(\hat{A}, \hat{T}) = \arg\max_{A, T} f(A, T|Y)$

- Main assumption: pulses not cropped
  - $\hat{A}$ does not depend on $T$
- Estimation of $\hat{A}$ → convex problem
  - Standard spectral unmixing of hyper/multi-spectral data
- Estimation of $\hat{T}|\hat{A}$: Multi-modal cost function but ...
  - Optimization on a regular grid

$\Rightarrow$ Fast linear unmixing and range estimation by integration of the 4D data cube over the temporal dimension
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Results

Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Spectral unmixing

- Identifying and quantifying the materials of the scene (range ≈ 1.80m)
- Acquisition time per pixel: 10 ms or 0.1 ms per band
- Here: 14 types of polymer clays + backboard

RGB image

Average photon counts
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Results

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Spectral unmixing

Figure: Example of estimated abundance maps
Results

Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Depth estimation
Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Depth estimation (≈ 10 photons per pixel and band)

- Posterior measure of uncertainty:

\[ p \left( d_n \in [\hat{d}_n - 0.5mm; \hat{d}_n + 0.5mm] \mid Y, \hat{A} \right) \]
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Results

Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Spectral unmixing (example II)

- Mixtures of natural and man-made objects

RGB image (5 × 5 cm)  Range profile (mm)
Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Spectral unmixing (example II)

Estimated abundances
Conclusion and future work

Conclusions

- Joint extraction of spectral and geometric information
- **Fast unmixing** using convex optimization
- Uncertainty about depth estimation

Future work

- Generalization to actual 3D unmixing → multiple surface detection
- Scanning system: sampling strategies
- Spectral analysis from extremely low photon counts
Thanks for your attention!
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