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Online Extrinsic Calibration of RGB and ToF Cameras for Extraterrestrial Exploration

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- Background
- Online Calibration
- Experiments

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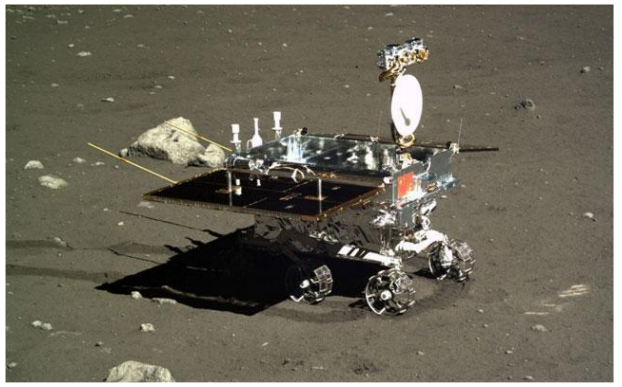
Background

Collaborative Perception Based on Multi-Sensor Information Fusion

- Unmanned System **Extraterrestrial Exploration Mission**
- Collaborative Perception Based on **Multi-Sensor Information Fusion**

The extraterrestrial scenes on Lunar surfaces.

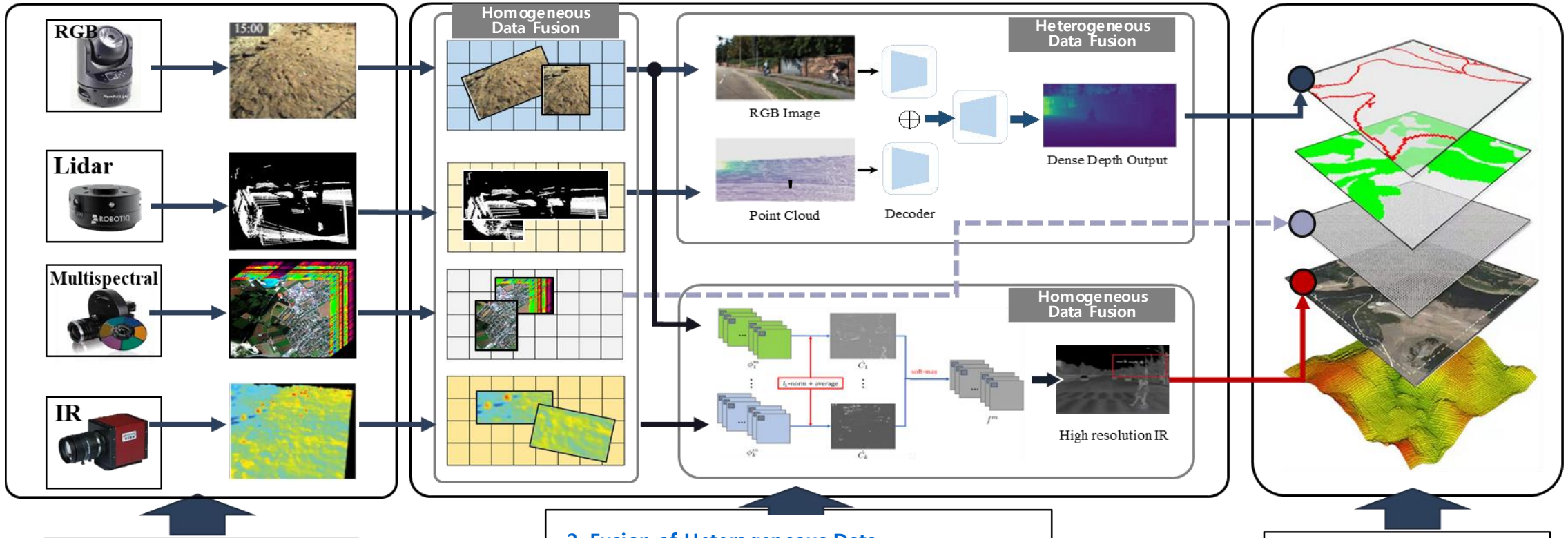
The extraterrestrial scenes on Martian surfaces.



Chinese lunar rover 'Yutu'.

Background

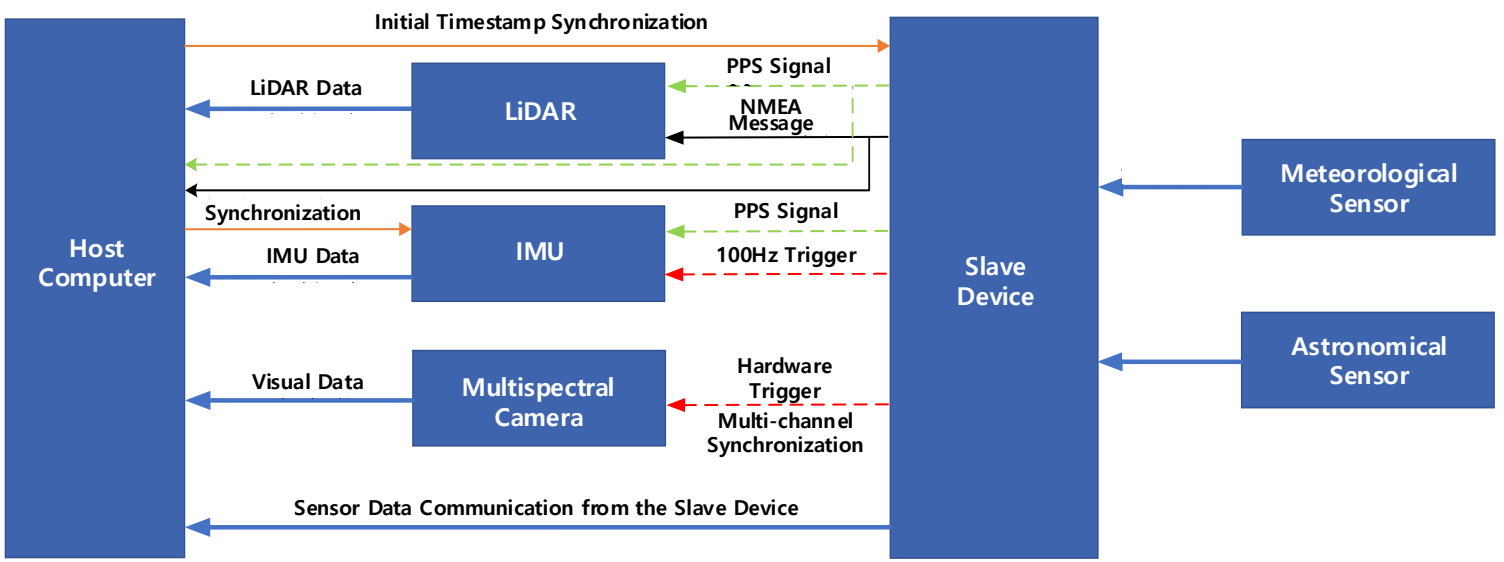
Collaborative Perception Based on Multi-Sensor Information Fusion



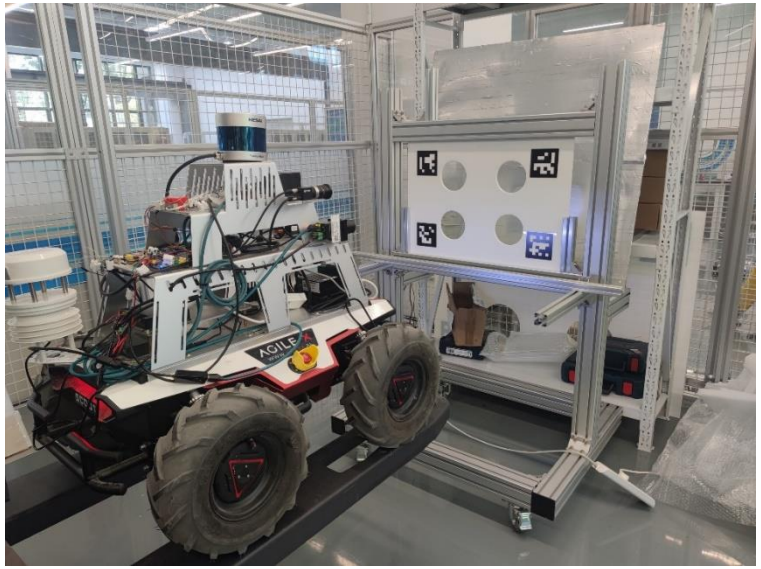
Background

Collaborative Perception Based on Multi-Sensor Information Fusion

- Multi-Sensor **Time Synchronization** for GNSS-Free Timing
- Multi-Sensor **Spatial Synchronization** using Pattern-based Calibration



Time Synchronization



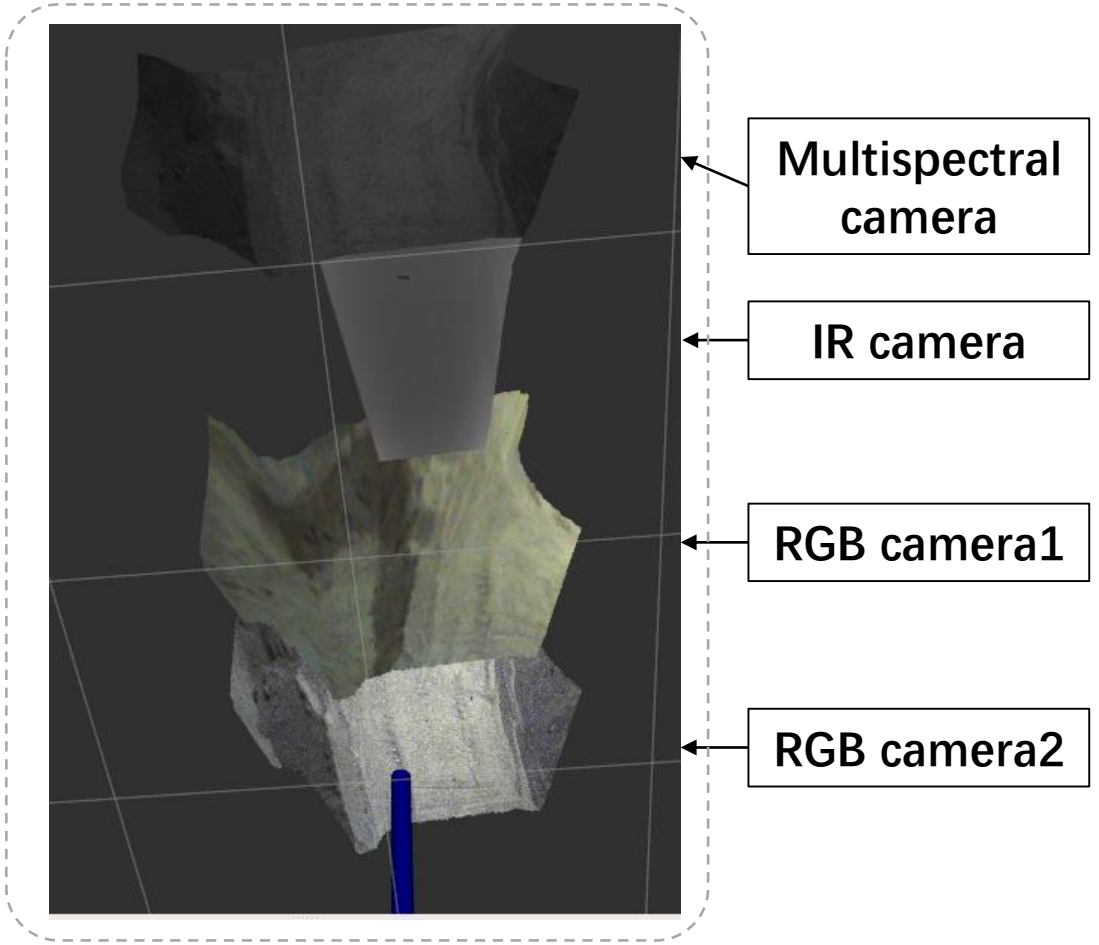
Spatial Synchronization

Background

Collaborative Perception Based on Multi-Sensor Information Fusion

Existing Problems during Exploration Task:

- **Inaccurate Alignment in Multi-Sensor Data Fusion**
- **Change of Sensor Configuration due to Vibration of the Rover**



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- **Online Calibration**
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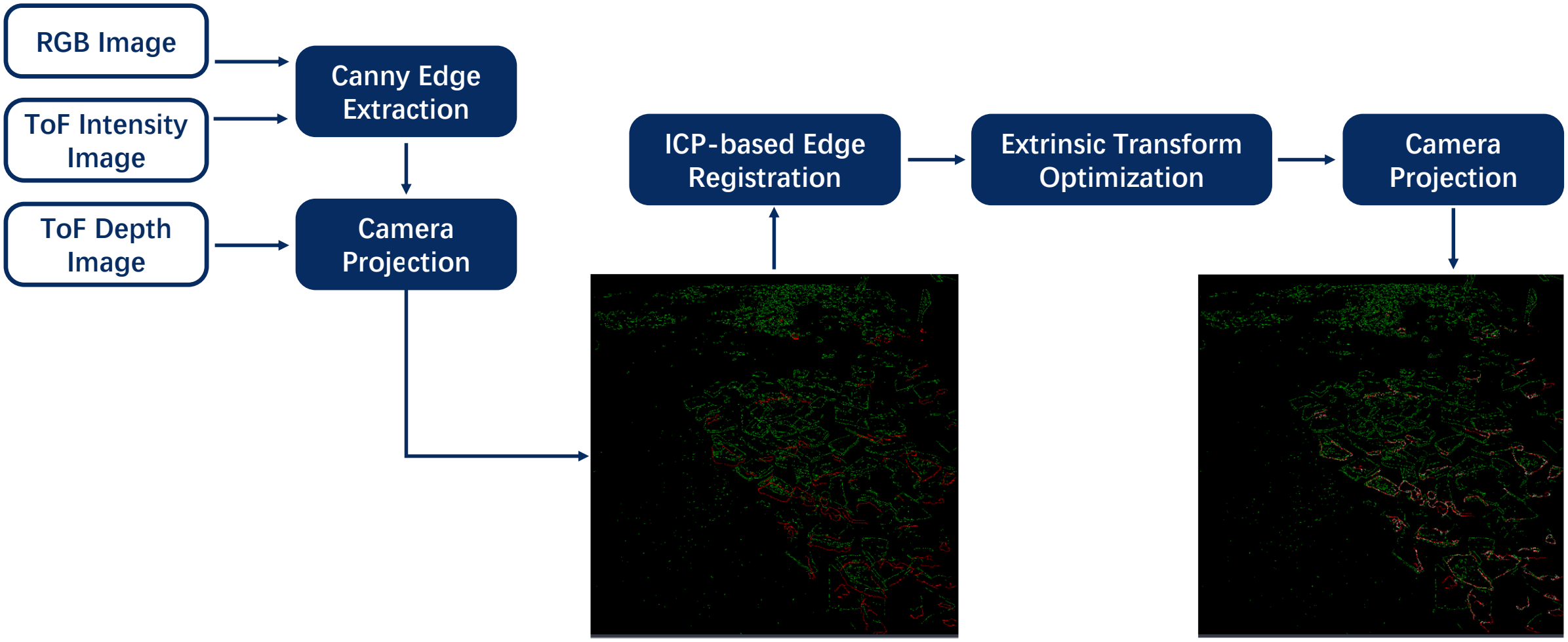
Online Calibration

Edge Registration-based Online Calibration



Online Calibration

Edge Registration-based Online Calibration

Camera Projection Model

- 3D point in the ToF camera coordinate system

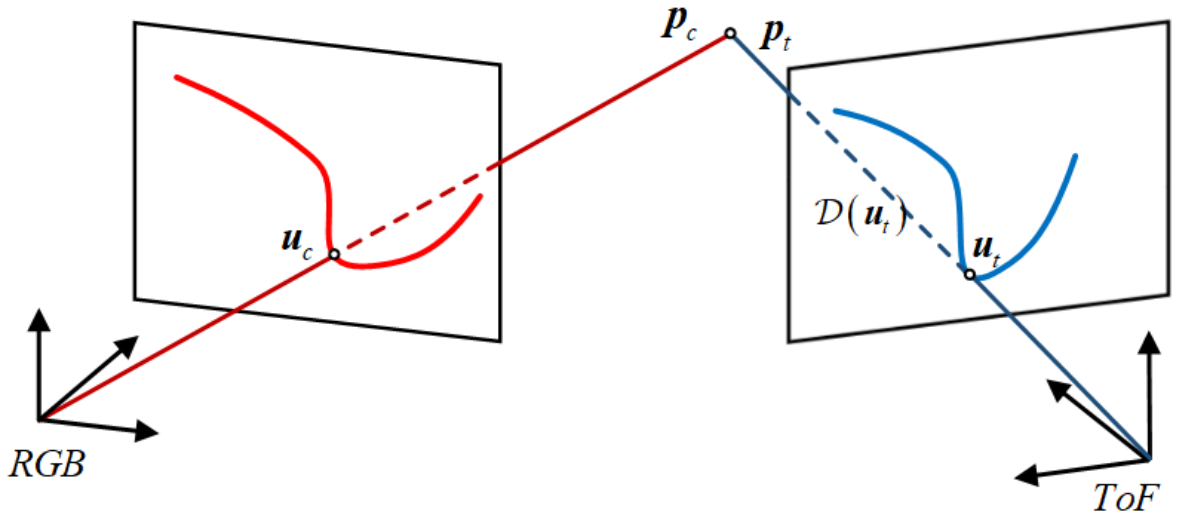
$$\boldsymbol{p}_t = \pi^{-1}\left(\boldsymbol{u}_t, \boldsymbol{K}_t, \mathcal{D}(\boldsymbol{u}_t)\right)$$

- 3D point in the RGB camera coordinate system

$$\boldsymbol{p}_c = \boldsymbol{R}_{ct}\boldsymbol{p}_t + \boldsymbol{t}_{ct}$$

- Pixel coordinates on the RGB image plane

$$\boldsymbol{u}_c = \pi\left(\boldsymbol{p}_c, \boldsymbol{K}_c\right)$$



Online Calibration

Edge Registration-based Online Calibration

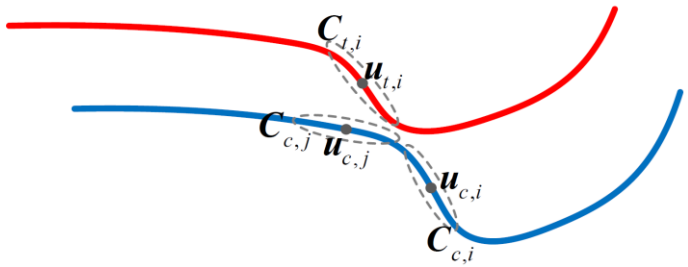
ICP-based Edge Registration

- The cost function for the 2D edge registration

$$E(\boldsymbol{T}_{ct}) = \sum_{i=1}^{N_c} \boldsymbol{r}_i^T \boldsymbol{C}_i \boldsymbol{r}_i$$

$$\boldsymbol{r}_i = \boldsymbol{u}_{c,i} - \pi\left(\boldsymbol{R}_{ct}\left(\pi^{-1}(\boldsymbol{u}_{t,i}, \boldsymbol{K}_t, \mathcal{D}(\boldsymbol{u}_{t,i}))\right) + \boldsymbol{t}_{ct}, \boldsymbol{K}_c\right)$$

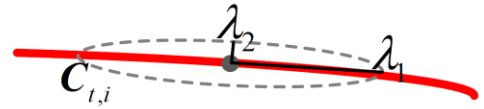
$$\boldsymbol{C}_i = \boldsymbol{C}_{c,i} + \boldsymbol{R}_{ct}\boldsymbol{C}_{t,i}\boldsymbol{R}_{ct}^T$$



(a)

- For a pixel on the edges, the eigenvalues satisfy $\lambda_1 \gg \lambda_2$

- Strong constraint along the normal direction aligning the edges strongly to each other along the normal



(b)

Online Calibration

Edge Registration-based Online Calibration

- **Extrinsic Transform Optimization**
  - In each iteration of the ICP-based edge registration, the cost function is optimized using Gauss-Newton algorithm.
  - Rewriting the cost function in a matrix style

$$E(\boldsymbol{T}_{ct}) = \boldsymbol{r}^T \boldsymbol{C} \boldsymbol{r}$$

$$\boldsymbol{r} = \begin{bmatrix} \boldsymbol{r}_1^T & \boldsymbol{r}_2^T & \cdots & \boldsymbol{r}_{N_c}^T \end{bmatrix}^T$$

$$\boldsymbol{C} = \begin{bmatrix} \boldsymbol{C}_1 & & & \\ & \boldsymbol{C}_2 & & \\ & & \ddots & \\ & & & \boldsymbol{C}_{N_c} \end{bmatrix}$$

  - An updated increment is computed by solving a second-order approximation

$$\delta \boldsymbol{\xi}^{(n)} = -(\boldsymbol{J}^T \boldsymbol{C} \boldsymbol{J})^{-1} \boldsymbol{J}^T \boldsymbol{C} \boldsymbol{r}$$

$$\boldsymbol{T}_{cr}^{(n+1)} = \exp(\delta \boldsymbol{\xi}^{(n)}) \boldsymbol{T}_{cr}^{(n)}$$

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Experiments

Edge Registration-based Online Calibration

- **Experiments on Accuracy**
  - **The extraterrestrial environment is mainly composed of sand and stones, which is challenging for the commonly used feature matching algorithm.**

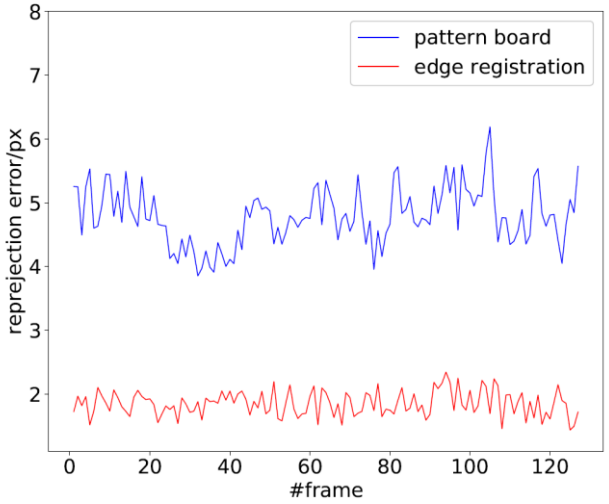
Sequence	Proposed method	Pattern board	OnlineCalib (Nonlinear Engineering2021)	GOM (IROS2013)	AutoCalib (ICCV2009)
Seq 1	**1.85px**	4.78px	failed	failed	failed
Seq 2	**1.82px**	4.88px	failed	failed	failed
Seq 3	**1.98px**	4.96px	failed	failed	failed
Seq 4	**1.54px**	4.83px	failed	failed	failed

The simulated extraterrestrial environment.

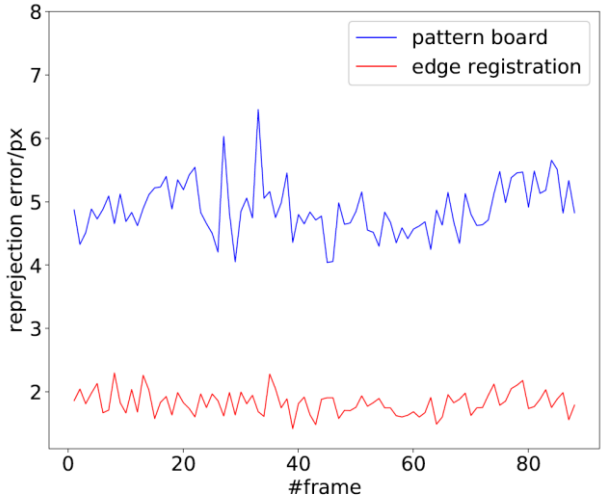
Experiments

Edge Registration-based Online Calibration

- **Experiments on Accuracy**
  - **re-projection errors of the proposed algorithm is much less than those of the traditional calibration procedure.**
  - **online calibration results can be automatically adjusted during the navigation missions, especially when the rover is running on the rugged terrain.**



(a) Sequence 1.

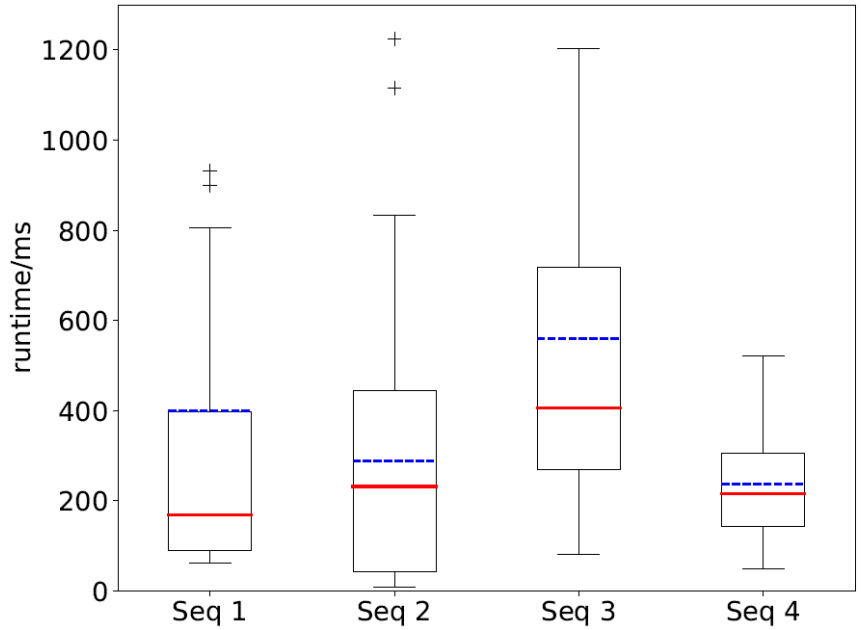


(b) Sequence 2.

Experiments

Edge Registration-based Online Calibration

- **Experiments on Runtime**
  - The real-time performance of the calibration algorithm is evaluated on the collected sequences.
  - The median and mean values of the runtimes for each sequence are labeled by red solid line and blue dotted line, respectively.



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Thank you !