# Progress Report

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# To be addressed

## Plane feature and projective shadow based SLAM

- Motivation
  - related work of plane based SLAM
  - common problems
- PFPS-SLAM framework
  - Map representation
  - Pose estimation
  - Loop closing
  - Map optimization
  - Map update

# Motivation

## related work

- Exploring High-Level Plane Primitives for Indoor 3D Reconstruction with a Hand-held RGB-D Camera, ACCV, 2013. [M. Dou, 2013]
- Dense Planar SLAM, ISMAR, 2014. [R. Salas-Moreno, 2014]
- Simultaneous Localization and Mapping with Infinite Planes, ICRA, 2015. [M. Kaess, 2015]
- CPA-SLAM: Consistent Plane-Model Alignment for Direct RGB-D SLAM, ICRA, 2016. [L. Ma, 2016]
- Pop-up SLAM: Semantic Monocular Plane SLAM for Low-texture Environments, IROS, 2016. [S. Yang, 2016]

# Motivation

**common problems**

- loop closing
- either based on other features or GPU

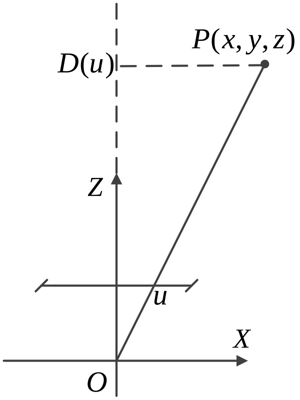
## Map representation

- Plane feature set $\left\{{}^{G}P_i\right\}_{i=1,\dots,N}$
- For each ${}^{G}P_i$
  - planes
    - plane parameters [M. Kaess, 2015]
      ${}^{G}\boldsymbol{\pi}_i = [{}^{G}\pi_{i1}, {}^{G}\pi_{i2}, {}^{G}\pi_{i3}, {}^{G}\pi_{i4}]^T \in \mathbb{P}^3$
    - plane center ${}^{G}\boldsymbol{p}_{\pi i}$
    - plane size $s_{\pi i}$
  - points on plane $\left\{{}^{G}\boldsymbol{p}_k^i\right\}$
  - salient points $\left\{{}^{G}\boldsymbol{p}_{sj}^i, {}^{G}\boldsymbol{a}_{sj}^i, (w_{sj}^i)\right\}$

## Map representation

- Determination of ${}^{G}\boldsymbol{a}_{sj}^{i}$
  - Measurement
    - Pixel coordinate $\boldsymbol{u} = [u, v]^T$
    - Depth map $D(\boldsymbol{u})$
    - Intensity map $I(\boldsymbol{u})$
  - Ray casting
    - $D(\boldsymbol{u})\dot{\boldsymbol{u}} = K\boldsymbol{p}$, $\dot{\boldsymbol{u}} = [\boldsymbol{u}, 1]^T$
    - define

$$\boldsymbol{\lambda}(\boldsymbol{u}) = K^{-1}\dot{\boldsymbol{u}} = \frac{\boldsymbol{p}}{D(\boldsymbol{u})}$$



# PFPS-SLAM

## Map representation

- Determination of ${}^{G}\boldsymbol{a}_{sj}^{i}$
  - Depth filter (in camera frame)

$$\delta(\boldsymbol{u}) = \frac{1}{N}\sum_{\boldsymbol{v}\in N(\boldsymbol{u})}[D(\boldsymbol{u}+\boldsymbol{v}) - D(\boldsymbol{u})]$$

$$\delta(\boldsymbol{u})\begin{cases} <0 & \text{if } \boldsymbol{p}'_s \\ >0 & \text{if } \boldsymbol{p}''_s \end{cases}$$

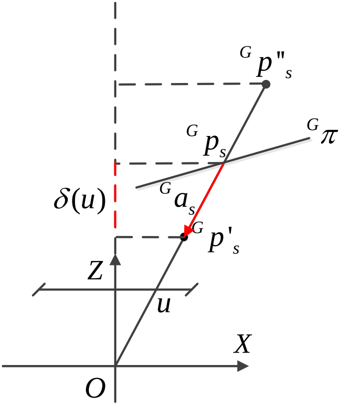
  - in global frame

$${}^{G}\boldsymbol{\lambda}(\boldsymbol{u}) = T_{gc}\cdot\boldsymbol{\lambda}(\boldsymbol{u})$$

$${}^{G}\boldsymbol{a}_s = {}^{G}\boldsymbol{\lambda}(\boldsymbol{u})\cdot\delta(\boldsymbol{u})$$

  - ${}^{G}\boldsymbol{a}_s$ satisfies

$${}^{G}\boldsymbol{p}'_s = {}^{G}\boldsymbol{p}_s + {}^{G}\boldsymbol{a}_s$$



# PFPS-SLAM

## Pose estimation

- projective data association [Y. Chen, 1992]
  - for a point ${}^r\boldsymbol{p}_s$ in reference frame
  - transform it into the current frame
  - if ${}^r\boldsymbol{a}_s^T\,{}^r\boldsymbol{n} > 0$

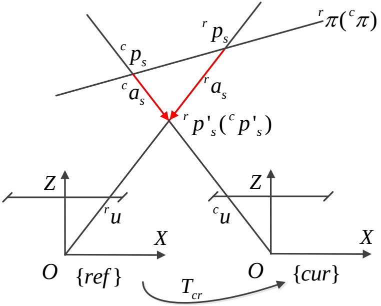
$$\begin{aligned} {}^c\boldsymbol{p}_s &= \mu\left({}^c\pi, {}^c\boldsymbol{p}_s'\right) \cdot {}^c\boldsymbol{p}_s' \\ &= \mu\left({}^c\pi, T_{cr}\left({}^r\boldsymbol{p}_s'\right)\right) \cdot T_{cr}\left({}^r\boldsymbol{p}_s'\right) \\ &= \mu\left({}^c\pi, T_{cr}\left({}^r\boldsymbol{p}_s + {}^r\boldsymbol{a}_s\right)\right) \cdot T_{cr}\left({}^r\boldsymbol{p}_s + {}^r\boldsymbol{a}_s\right) \end{aligned}$$

with

$$\mu(\pi, p_s') = \frac{d}{n^T(p_s')}$$

  - if ${}^r\boldsymbol{a}_s^T\,{}^r\boldsymbol{n} < 0$

$${}^c\boldsymbol{p}_s = T_{cr}\left({}^r\boldsymbol{p}_s\right)$$



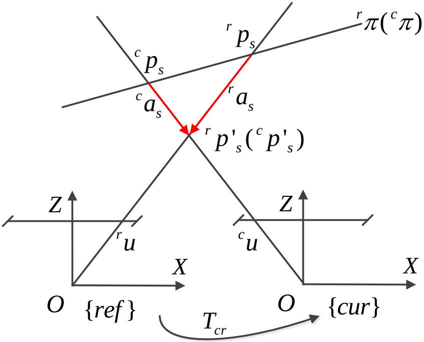
## Pose estimation

- projective data association
  - projecting ${}^c\boldsymbol{p}_s$ onto the image frame yields

$$ {}^c\boldsymbol{u} = \frac{1}{Z} K \cdot {}^c\boldsymbol{p}_s $$

  - measured point in current frame at pixel ${}^c\boldsymbol{u}$ is

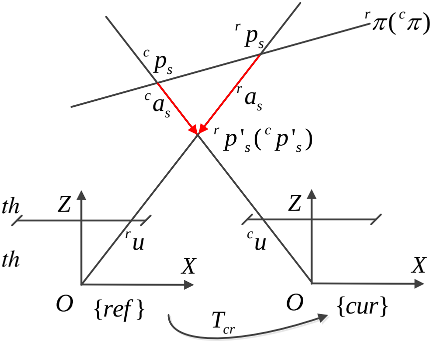
$$ {}^c\boldsymbol{p}_p = D_c({}^c\boldsymbol{u}) K^{-1}\, {}^c\dot{\boldsymbol{u}} $$



## Pose estimation

- projective data association
  - where the point ${}^{c}\boldsymbol{p}_p$ locates
    - on the plane ${}^{c}\pi$ corresponding to ${}^{r}\pi$
    - not on the plane
  - cost function

$$\varepsilon = \begin{cases} \left\| {}^{c}\boldsymbol{p}_p - {}^{c}\boldsymbol{p}_s \right\|_2^2 & if \ \left| {}^{c}\boldsymbol{p}_p^{T\,c}\boldsymbol{\pi} \right| \leq th \\ \left\| {}^{c}\boldsymbol{p}_p - {}^{c}\boldsymbol{p}_s - {}^{c}\boldsymbol{a}_s \right\|_2^2 & if \ \left| {}^{c}\boldsymbol{p}_p^{T\,c}\boldsymbol{\pi} \right| > th \end{cases}$$



# PFPS-SLAM

## Loop closing (small loops)

- formulation
  - for $k$-th frame
  - given $D_k(\boldsymbol{u})$, $T_{gk}$ and $\{{}^G P_i\}_{i=1,\ldots,N}$
  - using plane centers and sizes to determine which planes in the map could be measured by the $k$-th frame
- suppose $\{{}^G P_l\}_{l=1,\ldots,L}$ could be measured
  - build plane correspondences $\{{}^G P_m, {}^K P_m\}_{m=1,\ldots,M}$

# PFPS-SLAM

## Loop closing (small loops)

- for each salient point ${}^{G}\boldsymbol{p}_{sj}^{m}$ on ${}^{G}P_m$
  - if ${}^{G}\boldsymbol{a}_{sj}^{mT}\,{}^{G}\boldsymbol{n}_m > 0$

$$ {}^{K}\boldsymbol{p}_{sj}^{m} = \mu\left({}^{K}\pi_m, T_{gk}^{-1}\left({}^{G}\boldsymbol{p}_{sj}^{m} + {}^{G}\boldsymbol{a}_{sj}^{m}\right)\right) \cdot T_{gk}^{-1}\left({}^{G}\boldsymbol{p}_{sj}^{m} + {}^{G}\boldsymbol{a}_{sj}^{m}\right) $$

  - if ${}^{G}\boldsymbol{a}_{sj}^{mT}\,{}^{G}\boldsymbol{n}_m < 0$

$$ {}^{K}\boldsymbol{p}_{sj}^{m} = T_{gk}^{-1}\left({}^{G}\boldsymbol{p}_{sj}^{m}\right) $$

- project ${}^{K}\boldsymbol{p}_{sj}^{m}$ onto the image plane
  - the projected pixel coordinates are

$$ {}^{K}\boldsymbol{u} = \frac{1}{Z} K \cdot {}^{K}\boldsymbol{p}_{sj}^{m} $$

  - measured point in current frame at pixel ${}^{K}\boldsymbol{u}$ is

$$ {}^{c}\boldsymbol{p}_{pj}^{m} = D_k({}^{K}\boldsymbol{u}) K^{-1}\,{}^{K}\dot{\boldsymbol{u}} $$

## Loop closing (small loops)

- cost function

$$\varepsilon_m = \begin{cases} \left\| {}^K\boldsymbol{p}_{pj}^m - {}^K\boldsymbol{p}_{sj}^m \right\|_2^2 & \text{if } \left| {}^K\boldsymbol{p}_{pj}^{m\,T\,K}\pi \right| \leq th \\ \left\| {}^K\boldsymbol{p}_{pj}^m - {}^K\boldsymbol{p}_{sj}^m - {}^K\boldsymbol{a}_{sj}^m \right\|_2^2 & \text{if } \left| {}^K\boldsymbol{p}_{pj}^{m\,T\,K}\pi \right| > th \end{cases}$$

## Loop closing (global)

- formulation
  - local loop closing
    - for $k$-th frame
    - given $D_k(\boldsymbol{u})$, $\{{}^G P_i\}_{i=1,\ldots,N}$, $T_{gk}$
  - global loop closing
    - for $k$-th frame
    - given $D_k(\boldsymbol{u})$, $\{{}^G P_i\}_{i=1,\ldots,N}$
- 

## Map optimization

- plane features and projective shadows based bundle adjustment
- edge error definition
    - plane parameters

$$\varepsilon_p = \left\| h({}^{G}\pi_i, T_{gk}) \ominus {}^{K}\pi_i \right\|^2$$

with $\ominus$ represents the difference in tangent space [M. Kaess, 2015]

    - salient points

$$\varepsilon_s = \left| \left({}^{G}\boldsymbol{p}^{i}_{sj}\right)^T \left({}^{G}\boldsymbol{n}_i\right) \right| + \left| {}^{G}\boldsymbol{a}^{i}_{sj} \times \left(t_{gk} - {}^{G}\boldsymbol{p}^{i}_{sj}\right) \right|$$

# PFPS-SLAM

**Map update (plane fusion)**

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# Reference


- Y. Chen and G. Medioni. Object modeling by registration of multiple range images. Image and Vision Computing (IVC), 10(3):145155, 1992.
- M. Kaess, Simultaneous Localization and Mapping with Infinite Planes, ICRA, 2015.
- Lingni Ma, Christian Kerl, Jorg Stuckler and Daniel Cremers, CPA-SLAM: Consistent Plane-Model Alignment for Direct RGB-D SLAM, ICRA, 2016.
- Renato F. Salas-Moreno, Ben Glockery, Paul H. J. Kellyz and Andrew J. Davisonx, Dense Planar SLAM, ISMAR, 2014.
- Mingsong Dou, Li Guan, Jan-Michael Frahm, and Henry Fuchs, Exploring High-Level Plane Primitives for Indoor 3D Reconstruction with a Hand-held RGB-D Camera, ACCV, 2013.
- Shichao Yang, Yu Song, Michael Kaess, and Sebastian Scherer, Pop-up SLAM: Semantic Monocular Plane SLAM for Low-texture Environments, IROS, 2016.