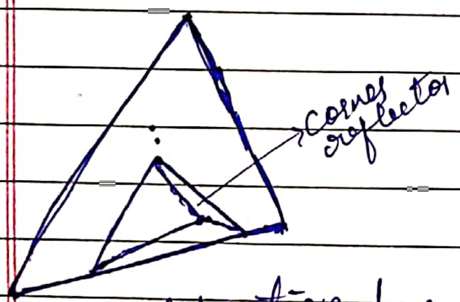
Extrinsic 6DOF Calibration of LiDAR and Radar

Extrinsic Radar - Lidar Calibration method

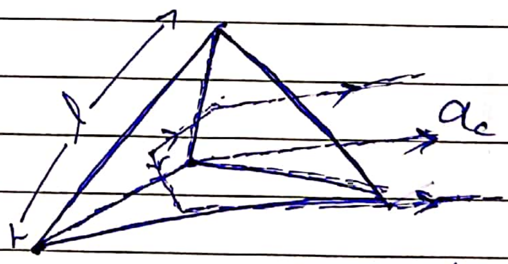
A. Calibration target design.

properties of well-designed targets are
1) ease of detection.
2) high localization accuracy for both sensors

For a radar, in order to accurately localize the source of detection, the target should be small as possible, hence used triangular tetrahedral corner reflector, which consists of 3 orthogonal flat metal triangles.



1a) Calibration target



1.b) Corner reflector

It has an interesting property that any reflected from all 3 sides is returned to the same direction as shown in fig1.b).

After three reflections, which form an orthonormal basis, the ray's direction is reversed. Due to this property, regardless of the incident angle, many rays are returned to their

Source, i.e the radar.

When the axis of the corner reflector α_c, points directly to the radar, it reaches the maximum Radar Cross Section (RCS) value:

$$\sigma_c = \frac{\pi l^4}{3\lambda^2} \quad (1)$$

$l \rightarrow$ hypotenuse length of a corner reflector's side.

$\lambda \rightarrow$ radar's operating wavelength.

However, from experiments presented, it can be seen that orientation changes of $\pm 20°$ results in a slight decrease of RCS, which can be approximated as a constant.

Corner reflector is visible to LiDAR, but is difficult to accurately localize it at greater distance due to its small size and complex shape.

This problem is solved by placing a flat triangle board in front of the reflector.

It is made up of 98% air resulting with low permittivity (1.10) & non conductiveness. these properties make virtually invisible to radar, but visible to LiDAR

Instead of rectangular shape, we use a triangular shape which can solve localization ambiguity issue caused by finite lidar resolution.

B. Correspondance registration

Correspondance registration in the data starts with the detection of the triangle in the point cloud.

The initial step is to segment plane candidates from which edge points are extracted. Afterwards, we try to fit these points to the triangle model.

Levenberg - Marquardt (LM) algorithm optimizes the pose of the triangle.

${}^{l}x_i \rightarrow$ position of the corner reflector origin.

Radar data of interest :

${}^{r}\phi_{r,i} \rightarrow$ detection angle.

${}^{r}\gamma_{r,i} \rightarrow$ range.

$\sigma_{r,i} \rightarrow$ radar cross section.

i^{th} object from the list is described by vector

${}^{r}m_i = [{}^{r}\phi_{r,i}, {}^{r}\gamma_{r,i}, \sigma_{r,i}]$ in the radar coord. frame, $F_r = ({}^{r}x, {}^{r}y, {}^{r}z)$

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To find the matching object, a rough initial calibration is required eg: with a measurement tape, which is used to transform the estimated corner position from the LiDAR coord frame, $F_l = (x, y, z)$ into F_r & eliminate all other objects that fall outside of the predefined threshold.

The target is observed at rest for a short period while the registered correspondance fill a correspondance group with a vector m_r, x_l.

Variances of radar data within group are used to determine the stability of the target.

If any of the variances surpasses a preset threshold, the correspondance is discarded. Otherwise the values are averaged.

In addition we create unregistered groups where radar detections are missing, these groups are used in the second optimization step where we refine the FoV.

Thereafter, we refer to the mean values of the groups as radar and lidar measurements.

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Two - step Optimization

A. Reprojection error optimization

Once the paired measurements are found, alignment of sensor coordinate frames is performed.

To ensure that the optimization performed on the radar measurements originating from the calibration target, we perform RCS threshold filtering.

we choose the threshold G_{RCS} close to the σ_c

The optimization parameter includes translation & rotation part i.e.

$$C_r = [\,^rP_l . \Theta\,].$$

for translation, we choose position of the LiDAR in the F_r,

$$^rP_l = [\,^rP_{x,l} . \,^rP_{y,l} ; \,^rP_{z,l}\,]^T$$

for rotation; we choose Euler angles repres.

$$\Theta = [\,\theta_z . \theta_y \;\; \theta_x\,]$$

where rotation from F_r to F_l is given by:

~~$R(\Theta) = R_x(\Theta_x) R_y$~~

$${}^{l}_{r}R(\Theta) = {}^{2}_{}R_x(\Theta_x)\, {}^{1}_{}R_y(\Theta_y)\, {}_{r}R_z(\Theta_z) \quad (2)$$

Radar provides measurements in spherical coordinates lacking elevation

${}^{r}s_{r,i} = [\, {}^{r}r_{r,i},\ {}^{r}\phi_{r,i},\ \sim]$, i.e. it provides an arc ${}^{r}a_{r,i}$ upon which the object potentially resides.

On the other hand, LiDAR provides a point in Euclidian coords ${}^{l}x_{l,i}$.

Using the current transformation estimate LiDAR measurement ${}^{l}x_{l,i}$ is transformed into the radar coord. frame:

$${}^{r}x_{l,i}(C_r) = {}^{lT}_{r}R(\Theta) \cdot {}^{l}x_{l,i} + {}^{r}P_l \quad (3)$$

then, ${}^{r}x_{l,i}$ is converted into spherical coord's:

$${}^{r}s_{l,i} = [\, {}^{r}r_{l,i}\ {}^{r}\phi_{l,i}\ {}^{r}\psi_{l,i}]$$

By neglecting the elevation angle ${}^{r}\psi_{l,i}$, we obtain the arc ${}^{r}a_{l,i}$ upon which the LiDAR measurements resides & can be compared to radar's.

Reprojection error $\epsilon_{r,i}$ is then defined as the Euclidean dist. of points on the arc for which ${}^{r}\varphi_{r,i} = {}^{r}\varphi_{l,i} = 0°$.

$$\epsilon_{r,i}(C_r) = \left\| \begin{bmatrix} {}^{r}r_{r,i} \cos({}^{r}\phi_{r,i}) \\ {}^{r}r_{r,i} \sin({}^{r}\phi_{r,i}) \end{bmatrix} - \begin{bmatrix} {}^{r}r_{l,i} \cos({}^{r}\phi_{l,i}) \\ {}^{r}r_{l,i} \sin({}^{r}\phi_{l,i}) \end{bmatrix} \right\| \quad (4)$$

using LM algorithm, we obtain the estimate of the Calibration parameter $\hat{C}_r$

by minimizing the sum of squared reprojection errors from N measurements.

$$\hat{C}_r = \arg\min_{C_r} \left(\sum_{i=1}^{N} \epsilon_{r,i}^{2}(C_r) \right) \quad (5)$$

optimization of described reprojection error yields unequal estimation uncertainty among the Calibration parameters.

$\therefore$ ${}^{r}p_{x,l}$, ${}^{r}p_{y,l}$ & θ_z can be properly estimated.

parameters ${}^{r}p_{z,l}$, θ_y and θ_x Causes smaller change in radar measurements. hence they are refined in the next step.

B. Field of View (FoV) optimization

To refine a parameter with high uncertainty we propose a second optimization step which uses addition information from RCS.

Vertical FoV of width $2 \cdot \psi_f$ is defined with 2 planes that go through the origin of F_r, P_U and P_D, with elevation angle $\pm \psi_{f}$.

The optimization parameter vector consist of a subset of transformation parameter & an RCS threshold, $C_f = [{}^r p_{z,l} \ \theta_y \ \theta_x \ \zeta_{RCS}]$

Other parameters are kept fixed.

After transforming a LiDAR measurement ${}^r x_{l,i}$ to F_r, the FOV error of i^{th} measurement $\epsilon_{f,i}$ is defined as:

$$\epsilon_{f,i}(C_f) = \begin{cases} 0, & \text{if inside FOV \& } \sigma_i > \zeta_{RCS} \\ d, & \text{if inside FOV \& } \sigma_i > \zeta_{RCS} \\ 0, & \text{if outside FOV \& } \sigma_i < \zeta_{RCS} \\ d, & \text{if outside FOV \& } \sigma_i < \zeta_{RCS} \end{cases} \quad (6)$$

where,

$$d = \min\{dist(P_U, {}^r x_{l,i}), dist(P_D, {}^r x_{l,i})\} \quad (7)$$

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Error is greater than '0' only if the LiDAR measurements falls inside the FoV when it should not according to threshold, E_f vice-versa.

Function dist (P, x) is defined as an unsigned distance from plane P to point x.

An estimate of Calibration parameters is obtained by minimizing the foll - cost function

$$\hat{C_f} = \underset{C_f}{\arg\min}\left(\sum_{i=1}^{N} \epsilon_{f,i}^{2}(C_f)\right) \quad (8)$$

Change of the threshold does not affect the cost function until at-least one measurement falls in or out of the FoV.