Scene mapping using a RGB-D sensor from an UAV

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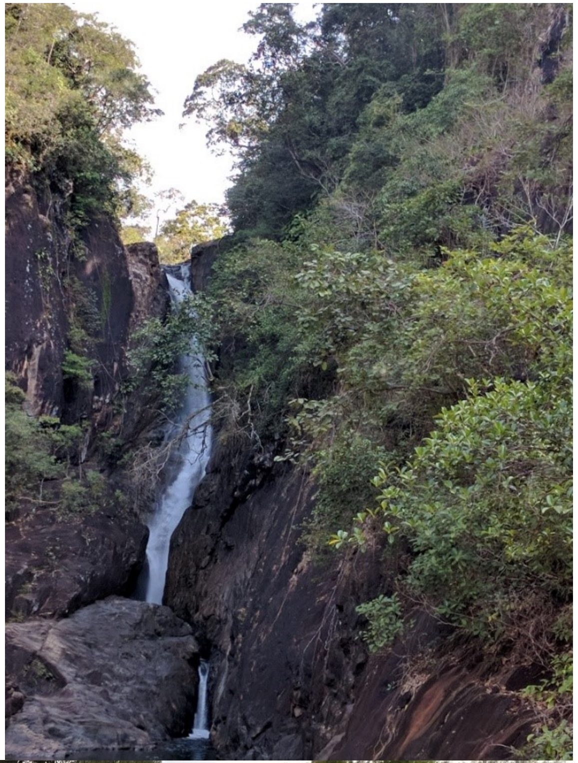
Motivation

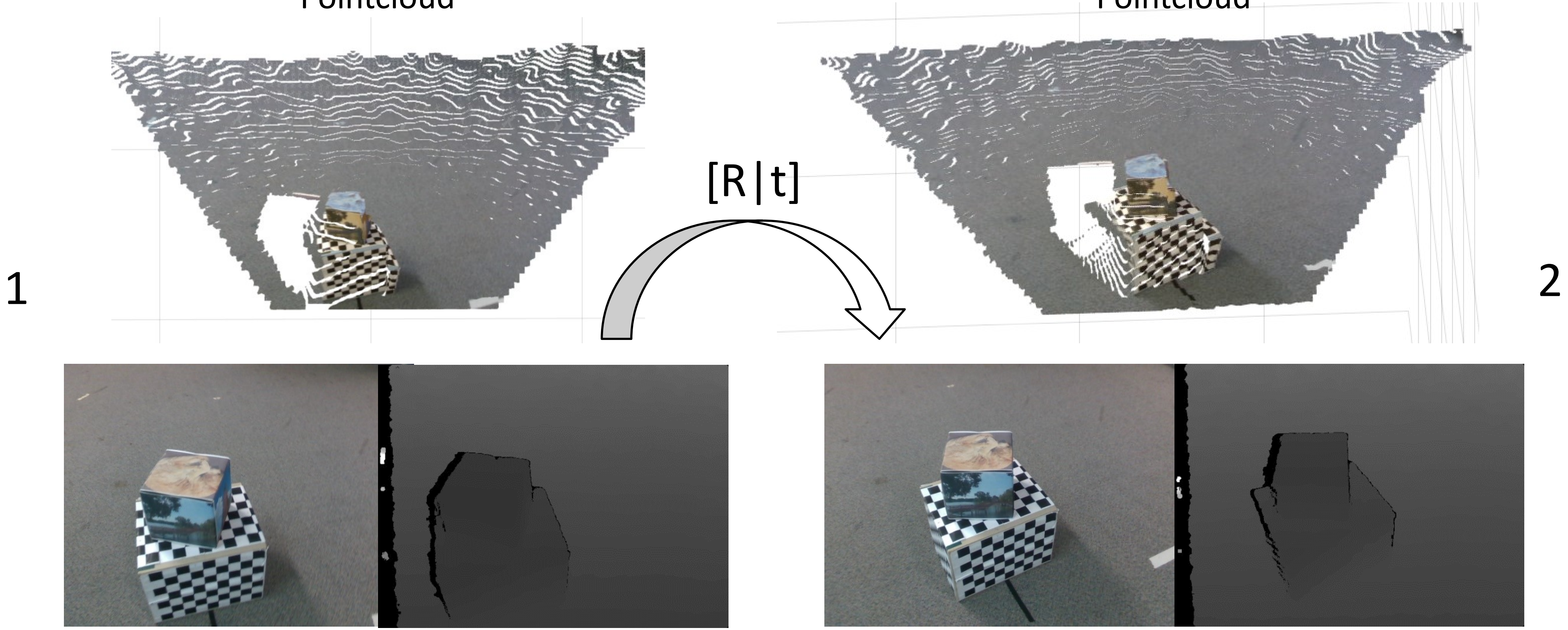
Unmanned Aerial Vehicle
(UAV)



Data registration

Pointcloud

Pointcloud



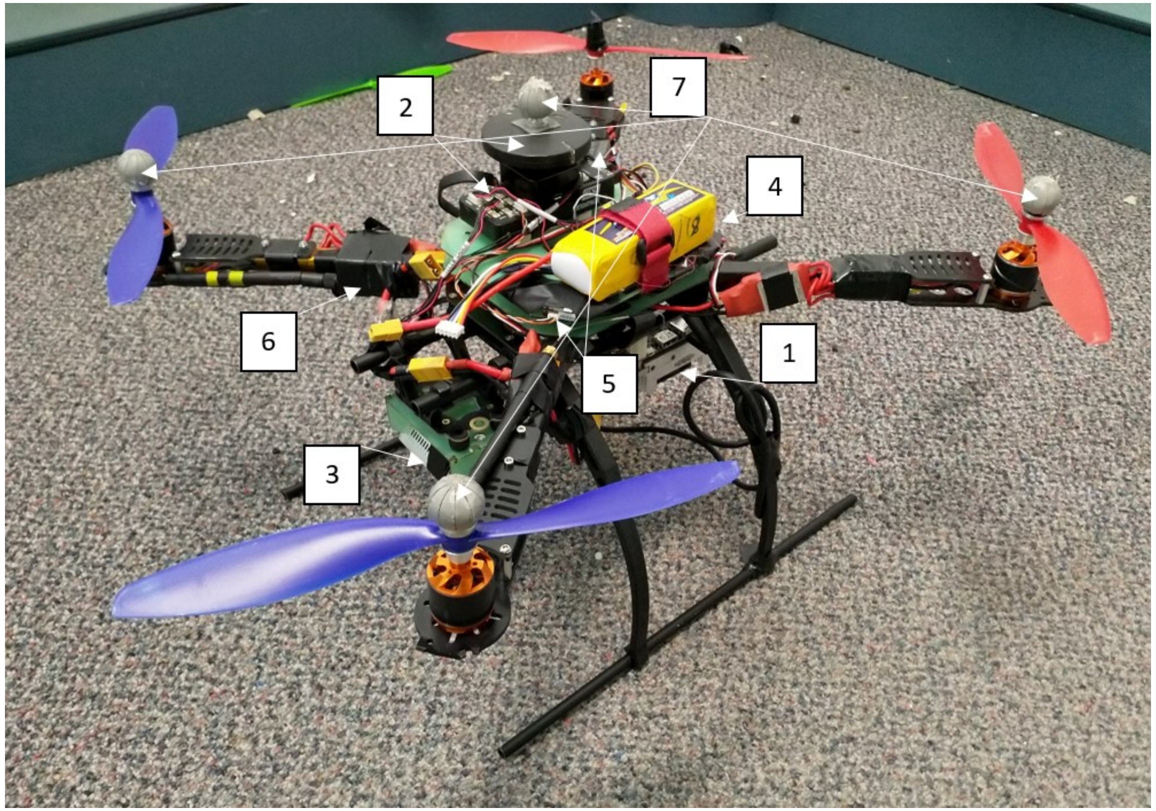
RGB image

Depth image
(brightened for visibility)

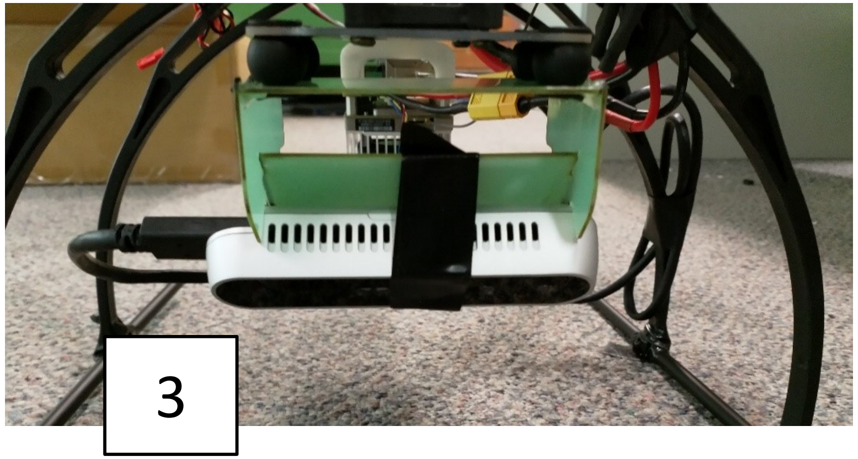
RGB image

Depth image
(brightened for visibility)

Building Quadcopter



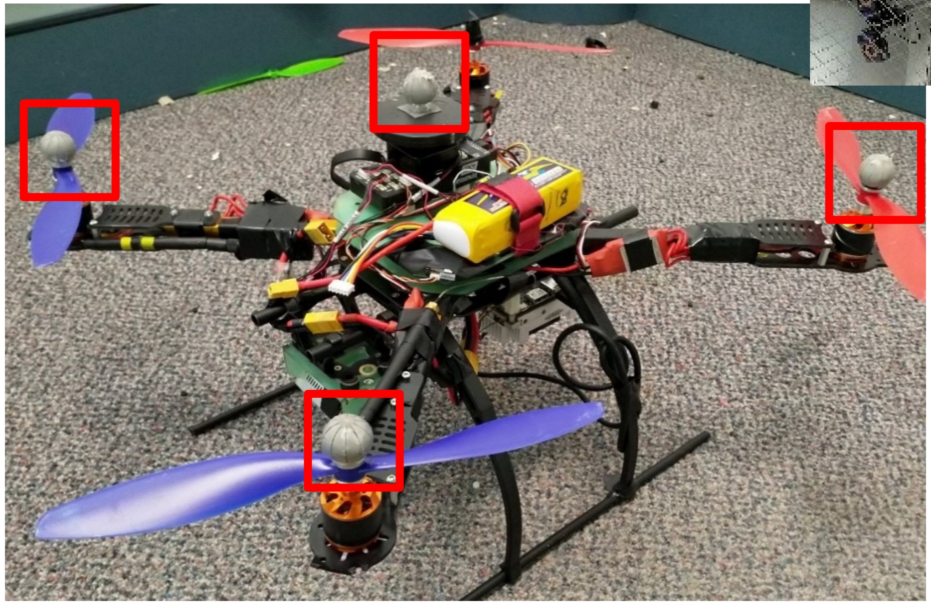
1. TX2 with Orbitty carrier board
2. Pixhawk 4 flight controller and GPS
3. RealSense camera with fixed mount
4. Lithium polymer battery
5. Receiver
6. Radio
7. Vicon markers



Vicon system

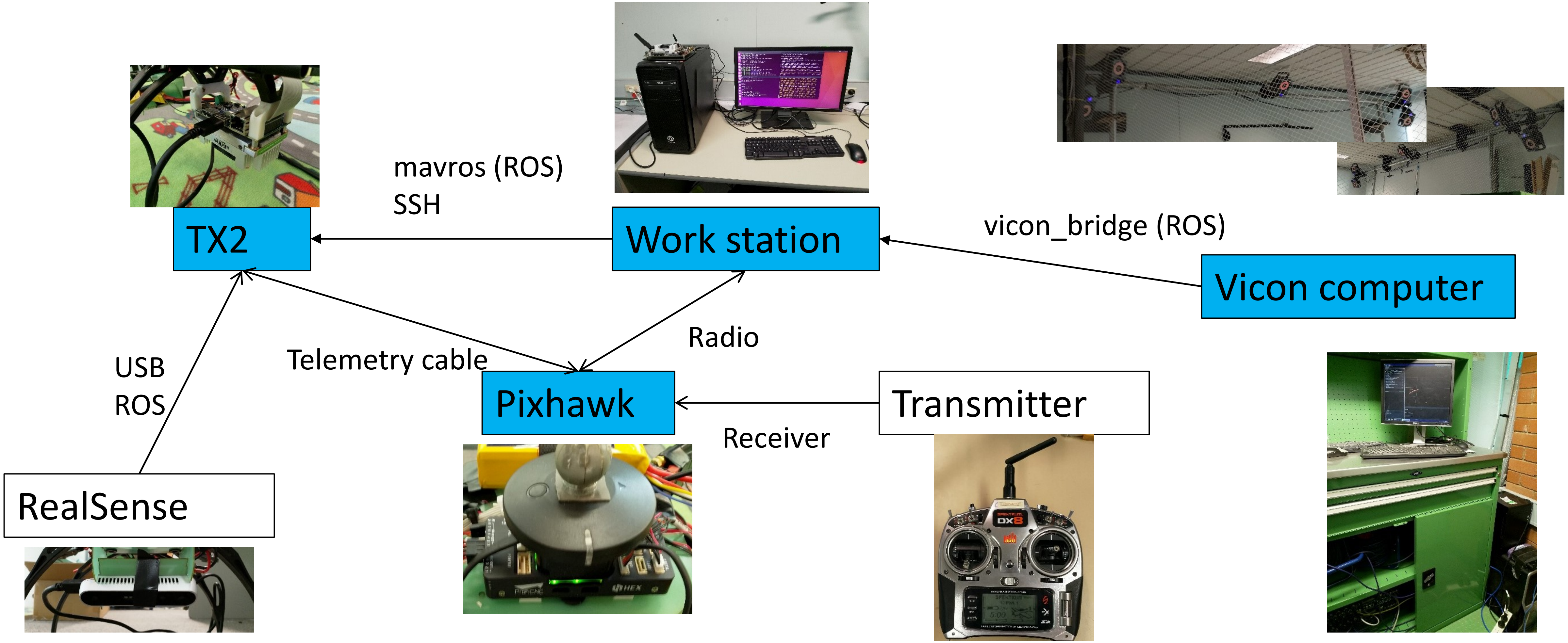
IR cameras

Vicon computer



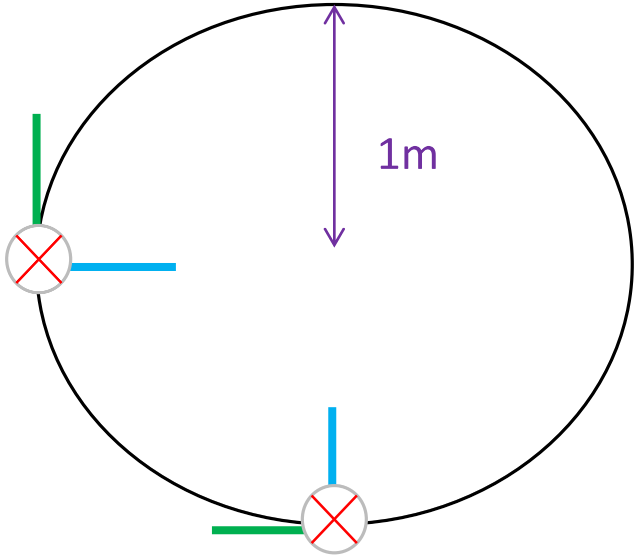
Vicon markers

System


TX2
mavros (ROS)
SSH
Work station
vicon_bridge (ROS)
Vicon computer
USB
ROS
Telemetry cable
Radio
Pixhawk
Transmitter
Receiver
RealSense

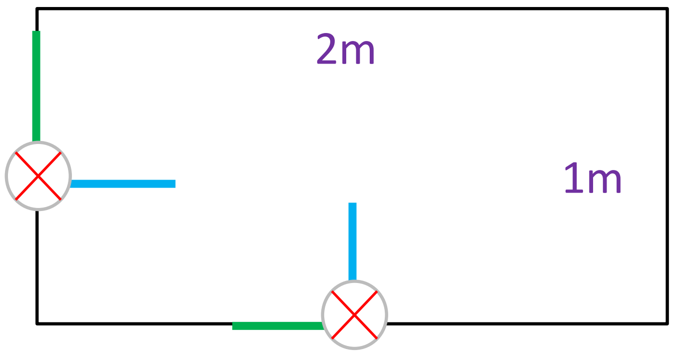
Collecting data - trajectories

Circle



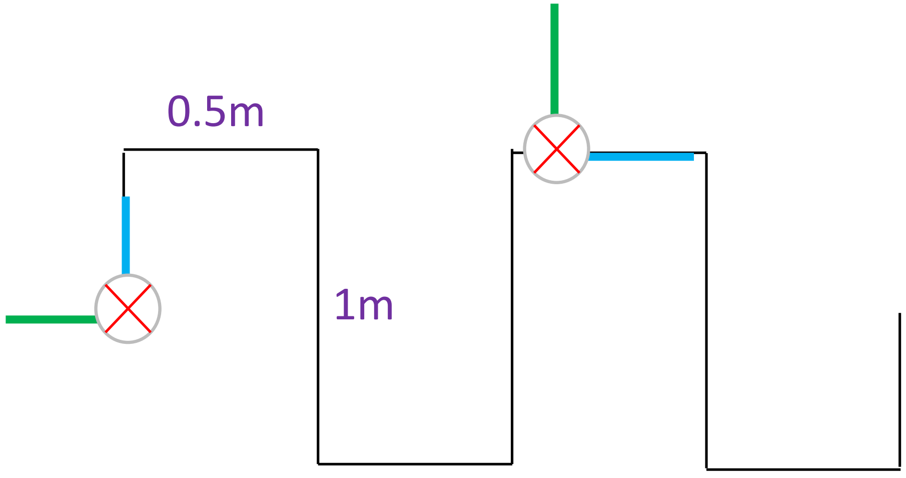
2 loops
Quad facing inwards

Rectangle



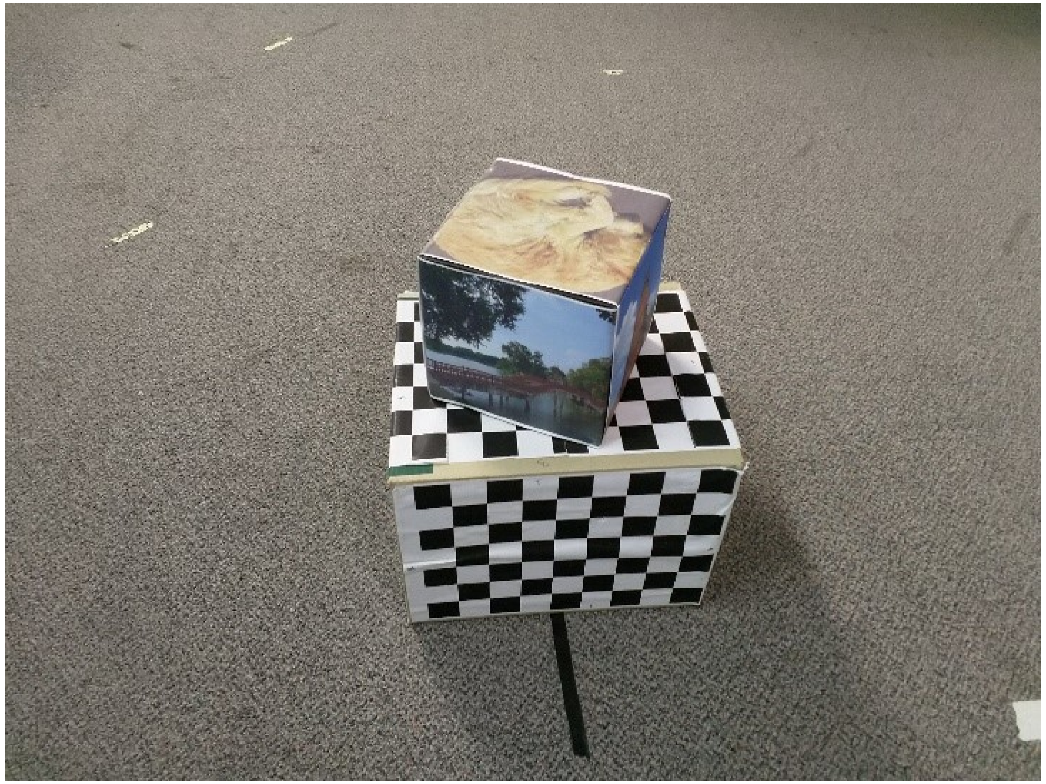
2 loops
Quad facing inwards

Lawnmower

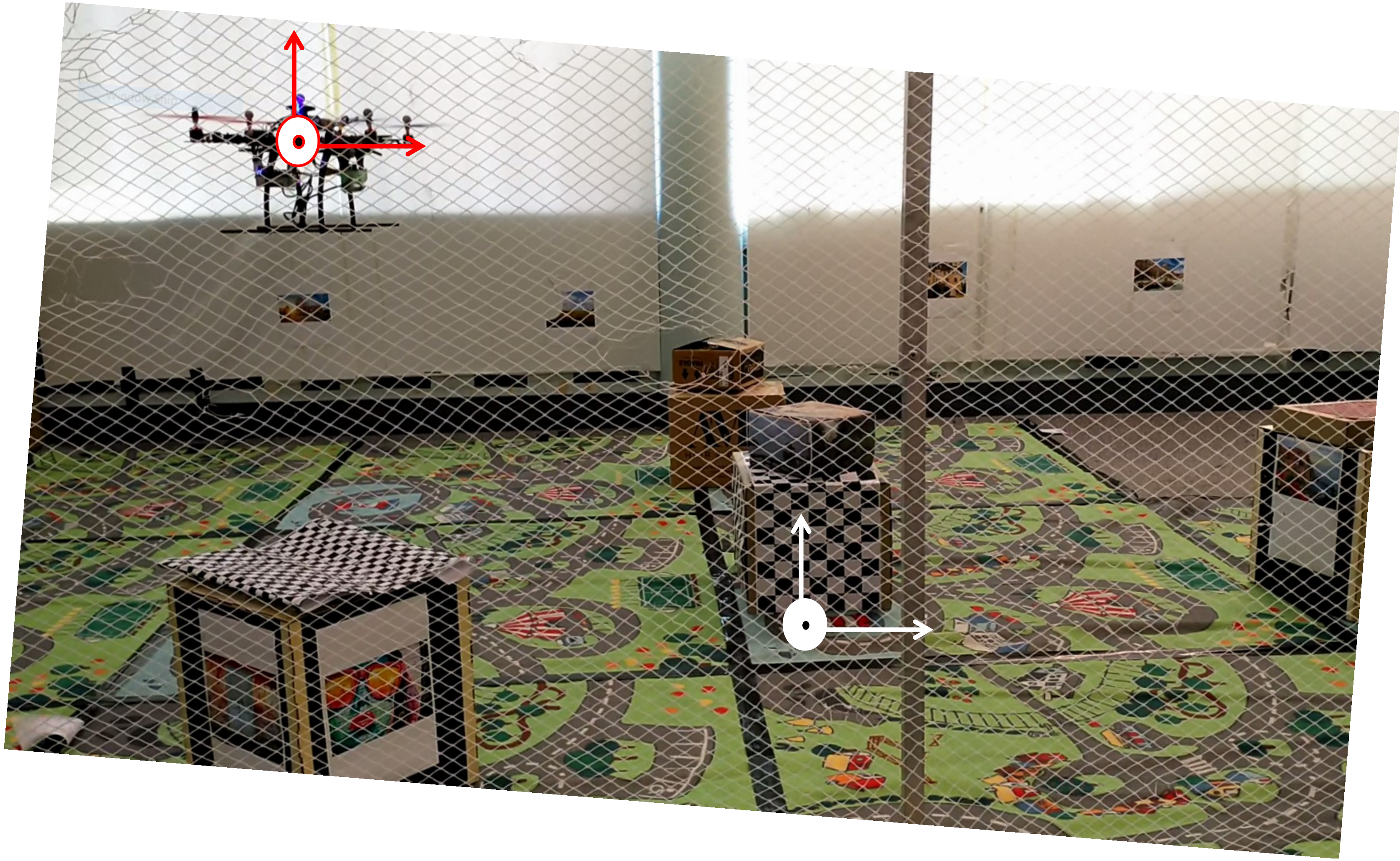


Mirrored trajectory back
Quad facing forwards

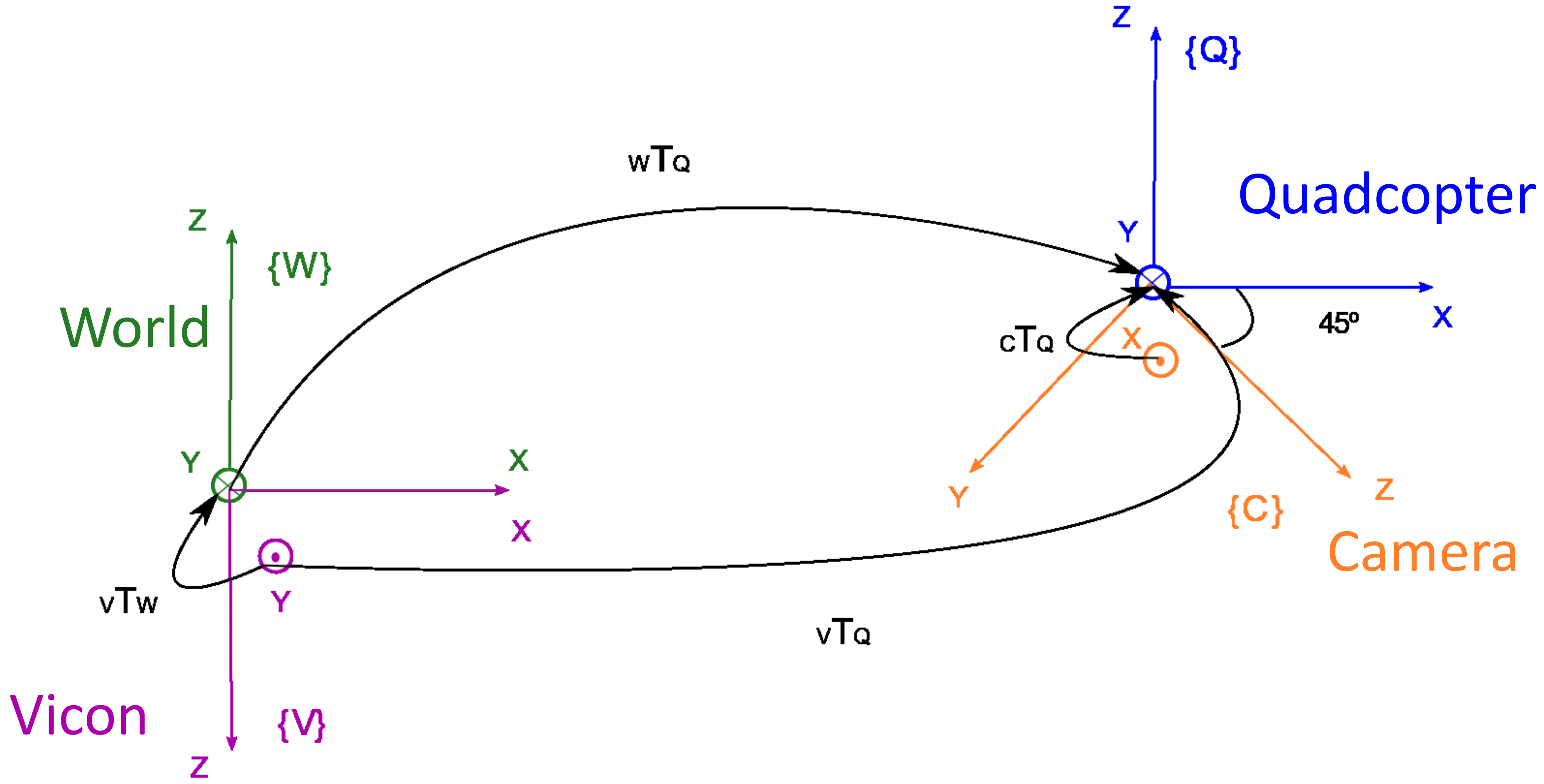
Collecting data - Scene



Frames

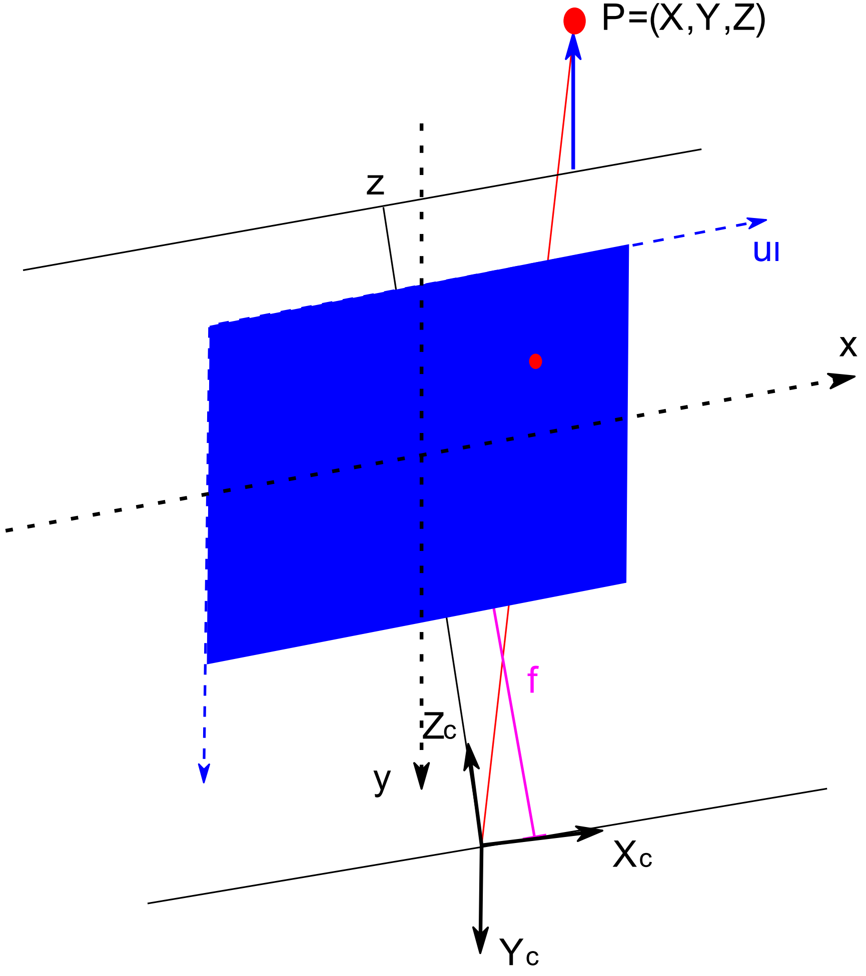


Frames

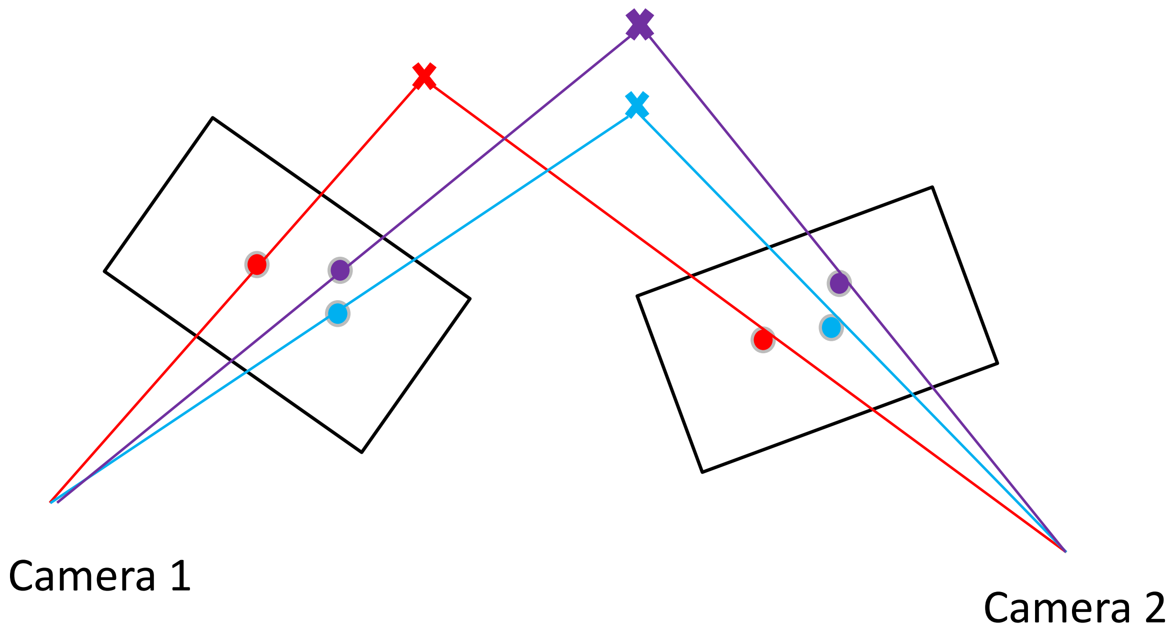


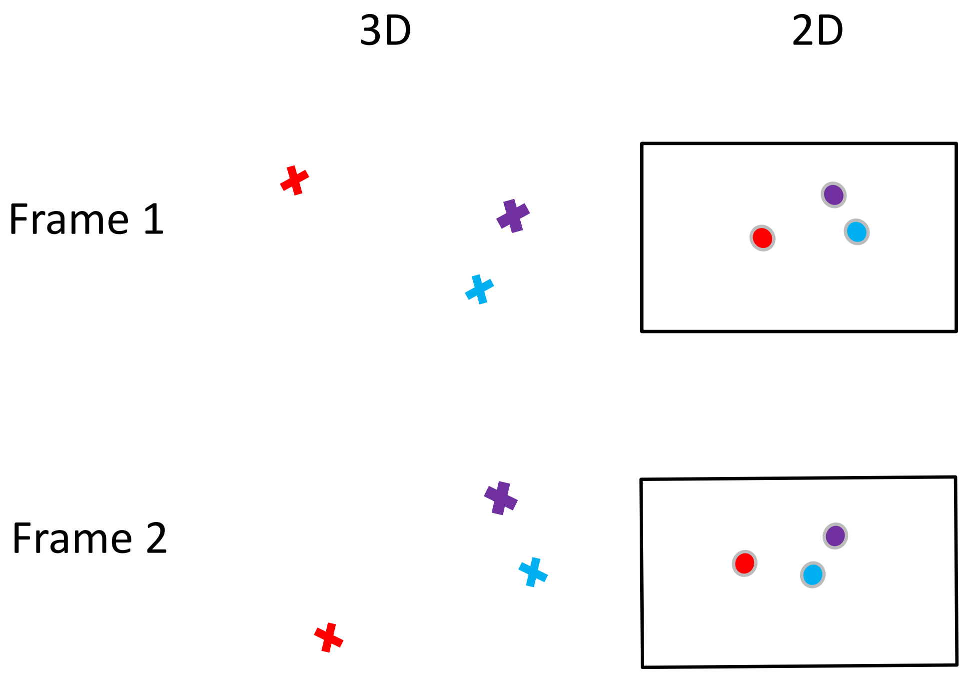
Z
{Q}
wTQ
Quadcopter
Z
{W}
Y
World
X
cTQ
45º
X
X
Y
X
Y
Y
Z
X
{C}
Camera
vTW
Y
vTQ
Vicon
{V}
Z

Frames



Projective geometry





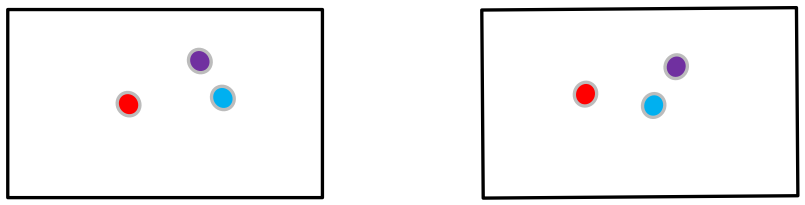
Registration techniques

Essential Matrix

RGB data

Epipolar geometry

Nister’s 5-point algorithm (Nister 2003)



Kabsch

3D data

3D point cloud registration for known correspondences

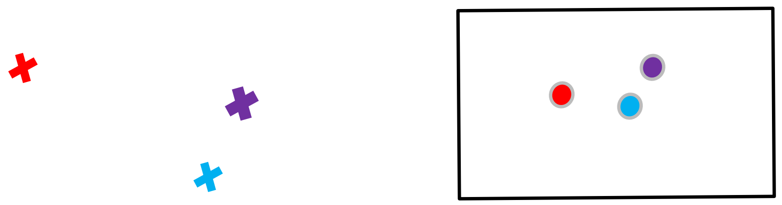
SVD implementation (Kavraki 2009)

PnP

2D and 3D data

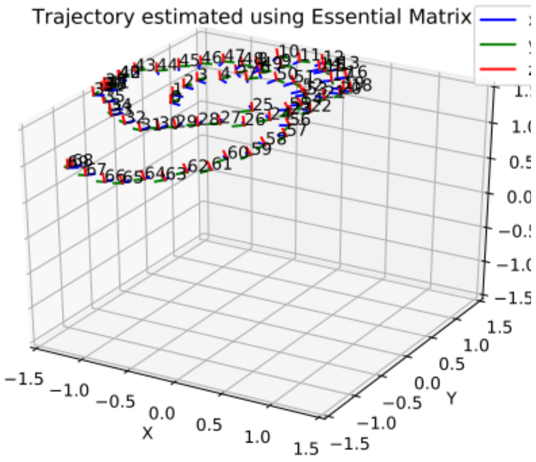
Projective geometry

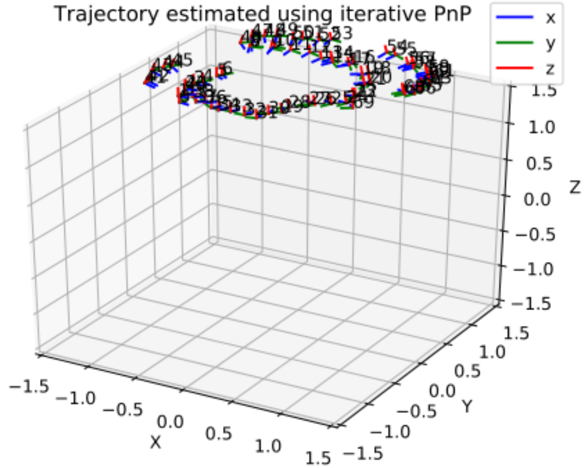
EPnP (Lepetit 2009)

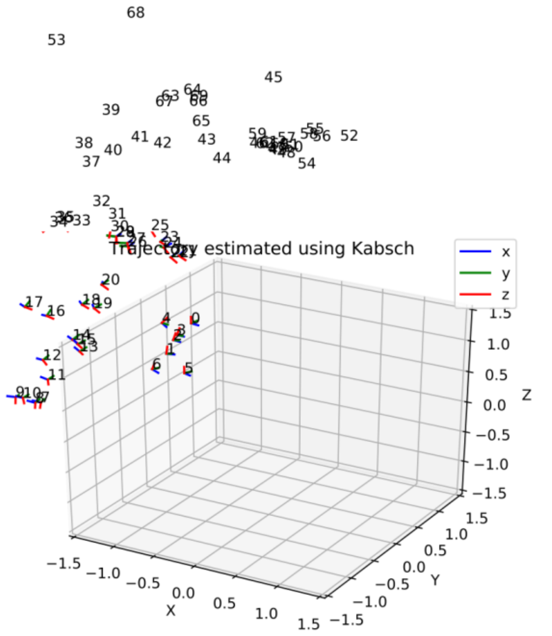


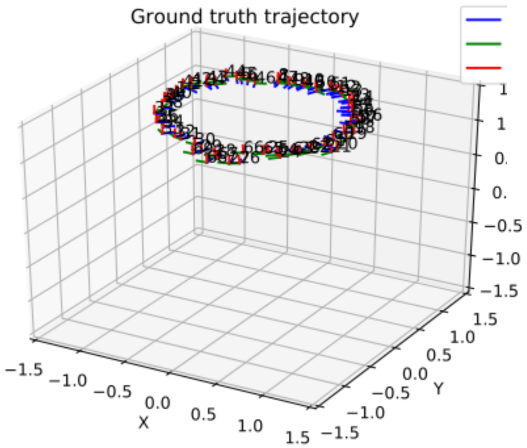
Results – processing frequency

30 frames skipped

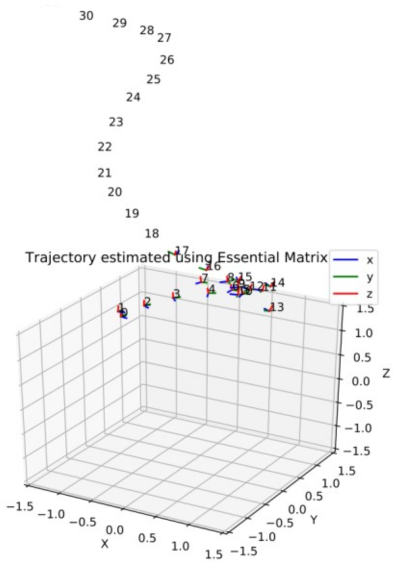


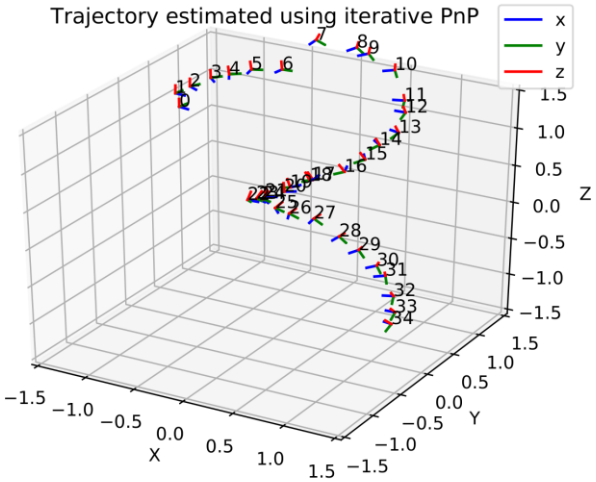


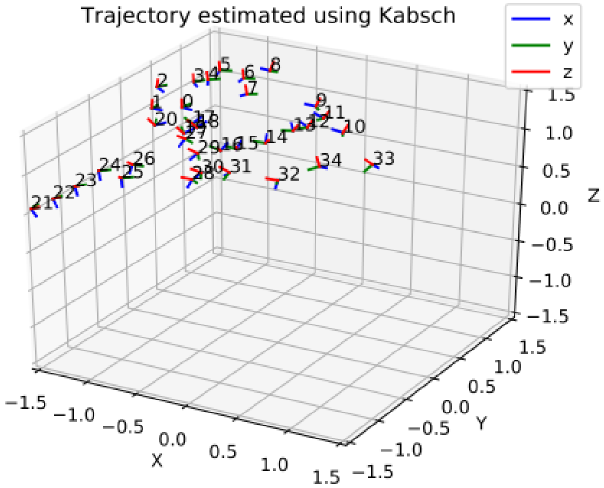




60 frames skipped







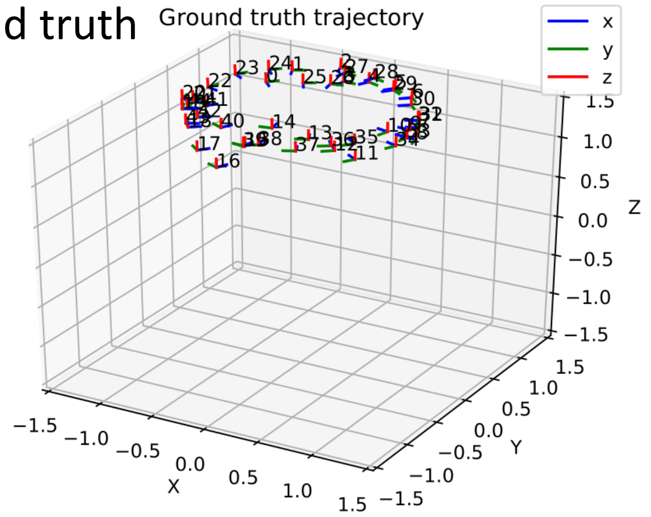
Essential Matrix

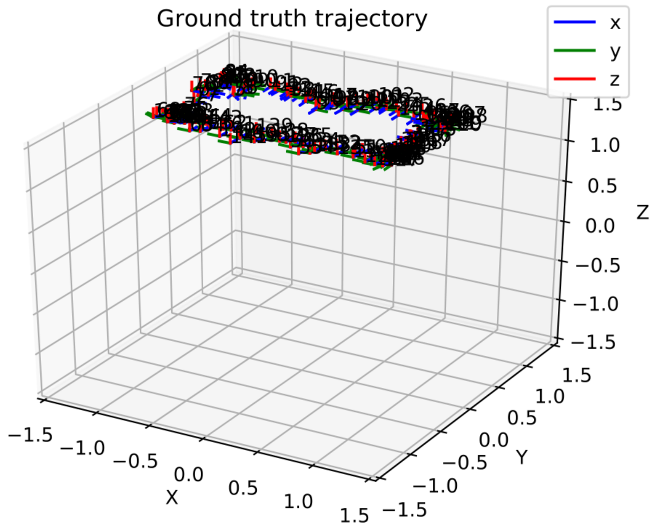
PnP

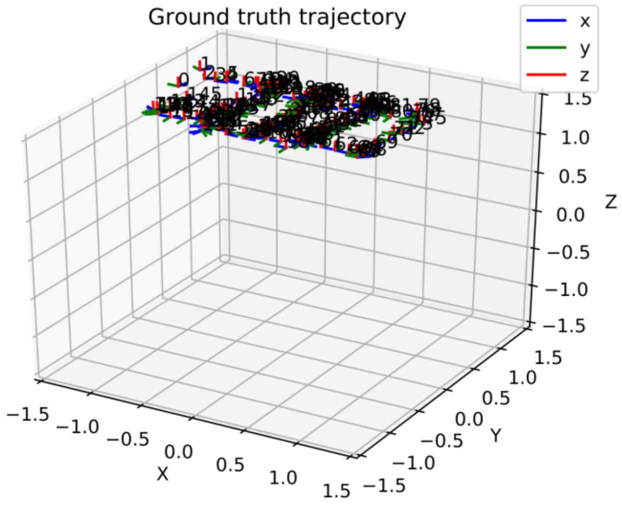
Kabsch

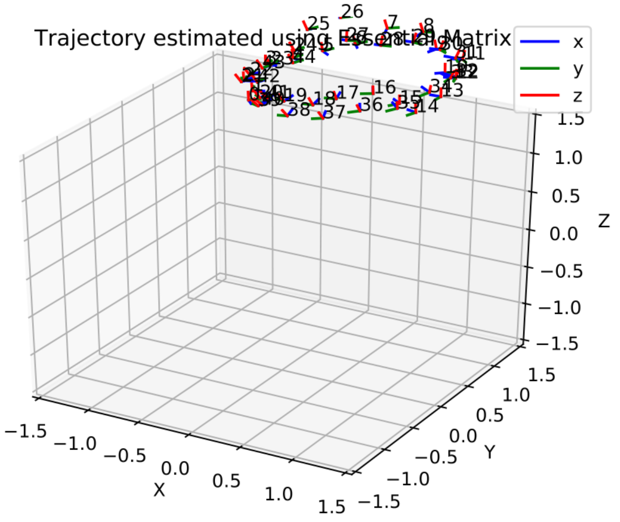
Results - trajectories

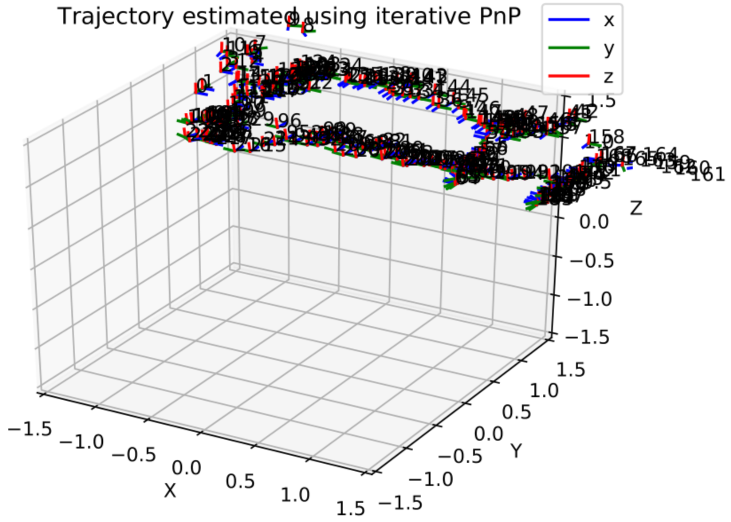
Ground truth

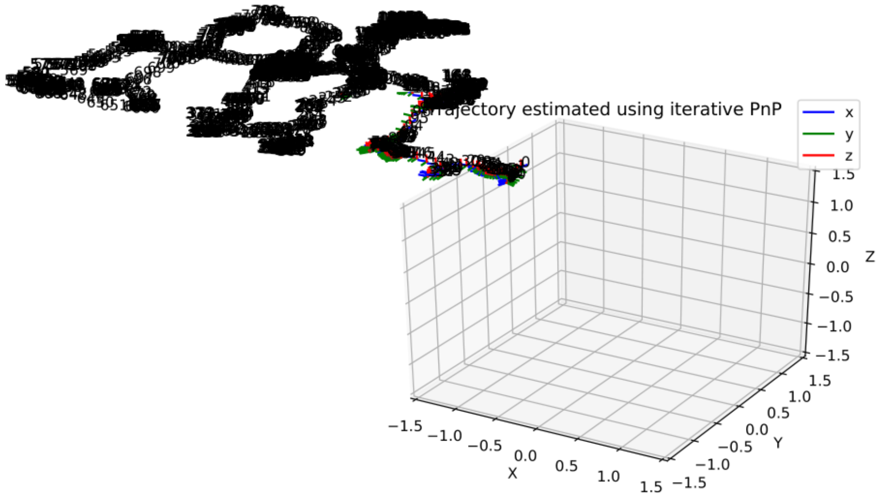












Best estimated trajectory

Conclusions and future work

Conclusions

- PnP has better accuracy than the Essential Matrix method for the rectangular and lawnmower trajectories, and is similar for the circular one.
- PnP is slow
- For large motions Kabsch may be better

Extending mapping algorithm

- Mapping algorithms often use multiple registration methods
- Registration is only one part of mapping – choosing frames, closing loop

References

D. Nister. An efficient solution to the five-point relative pose problem. In Computer Vision and Pattern Recognition, 2003. Proceedings. 2003 IEEE Computer Society Conference on, volume 2, pages II–195. IEEE, 2003.

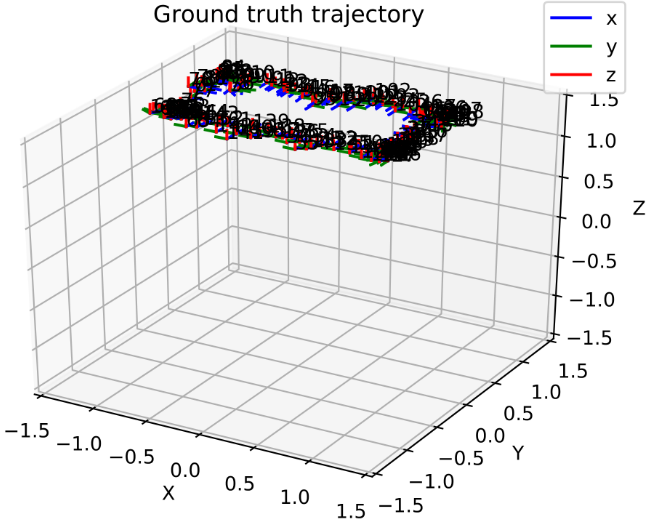
L. E. Kavraki. Geometric methods in structural computational biology. 2009.

V. Lepetit, F. Moreno-Noguer, and P. Fua. Epnp: An accurate o (n) solution to the pnp problem. International journal of computer vision, 81(2):155, 2009.

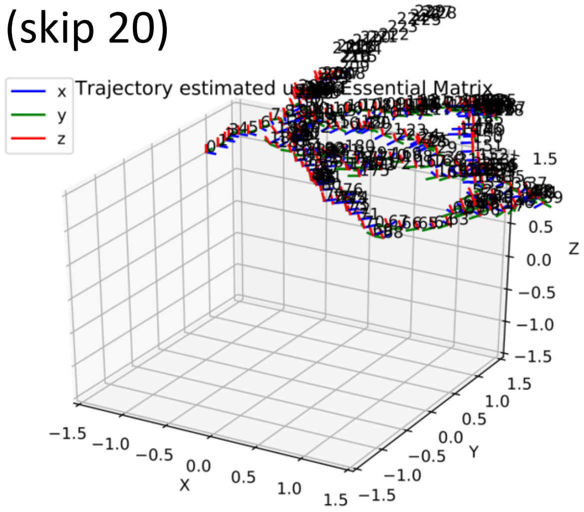
Questions

Results – rectangle trajectory

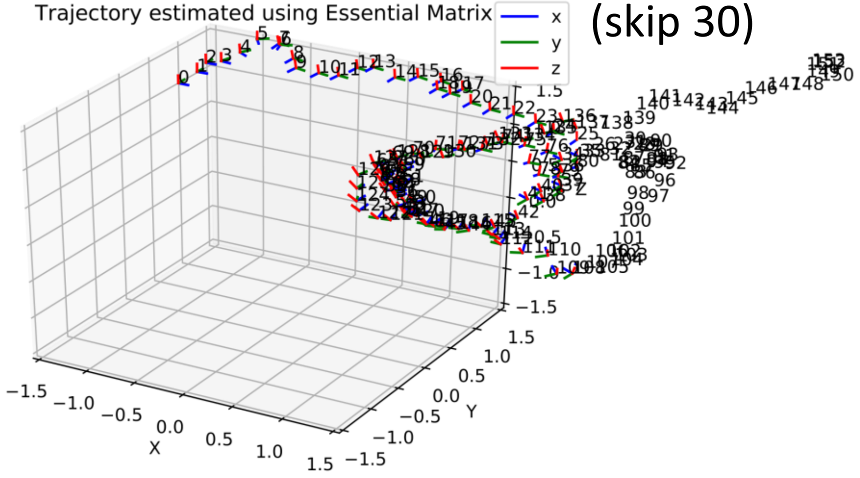
Ground truth

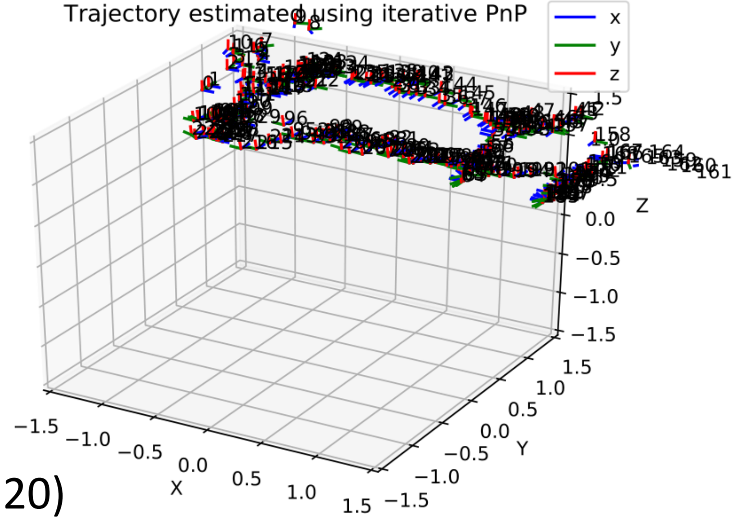


Essential Matrix
(skip 20)

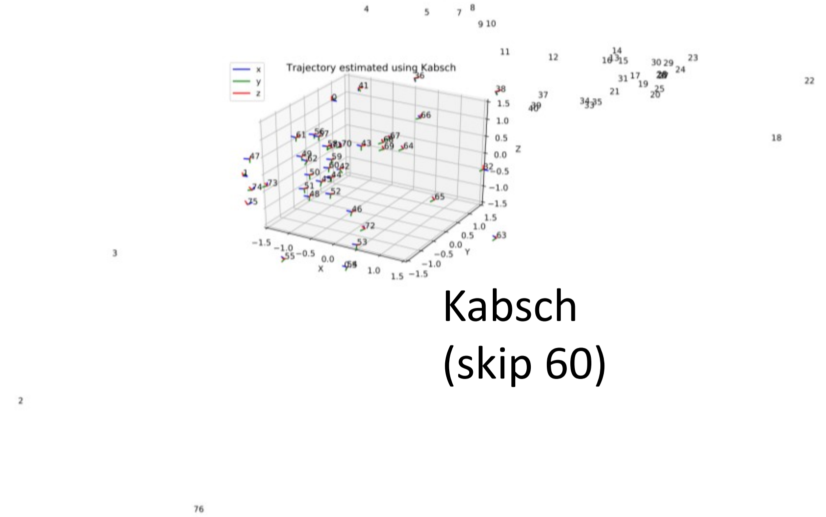


Essential Matrix
(skip 30)





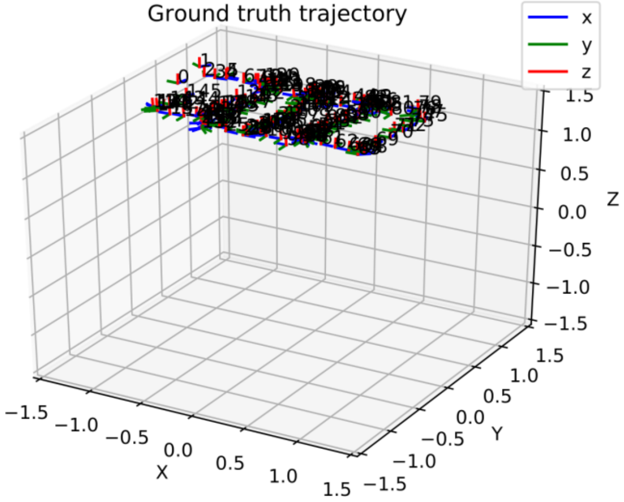
PnP (skip 20)



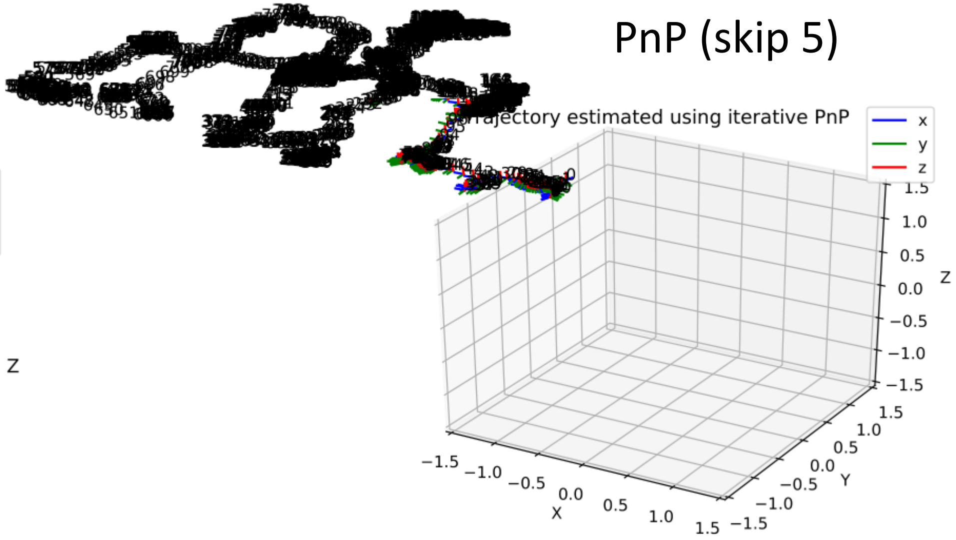
Kabsch
(skip 60)

Results – lawnmower

Ground truth

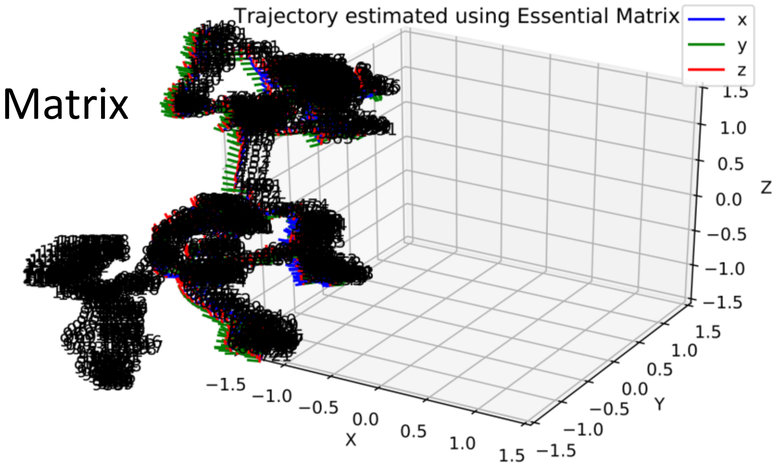


PnP (skip 5)

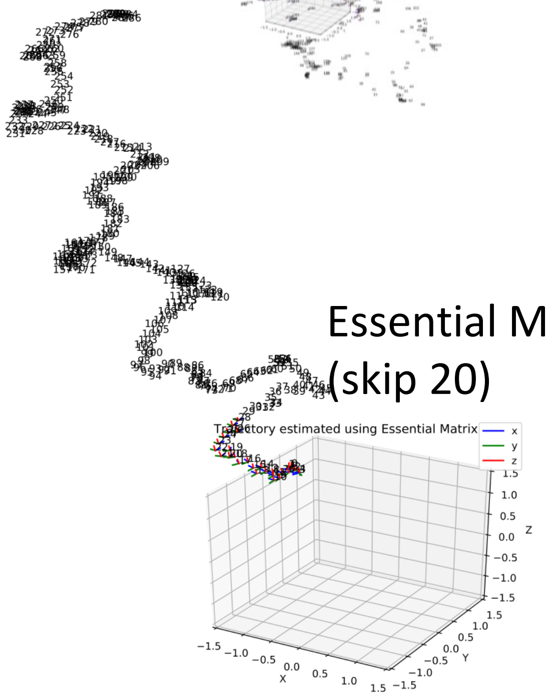


Kabsch (skip 5)

Essential Matrix (skip 5)



Essential Matrix (skip 20)



RANSAC

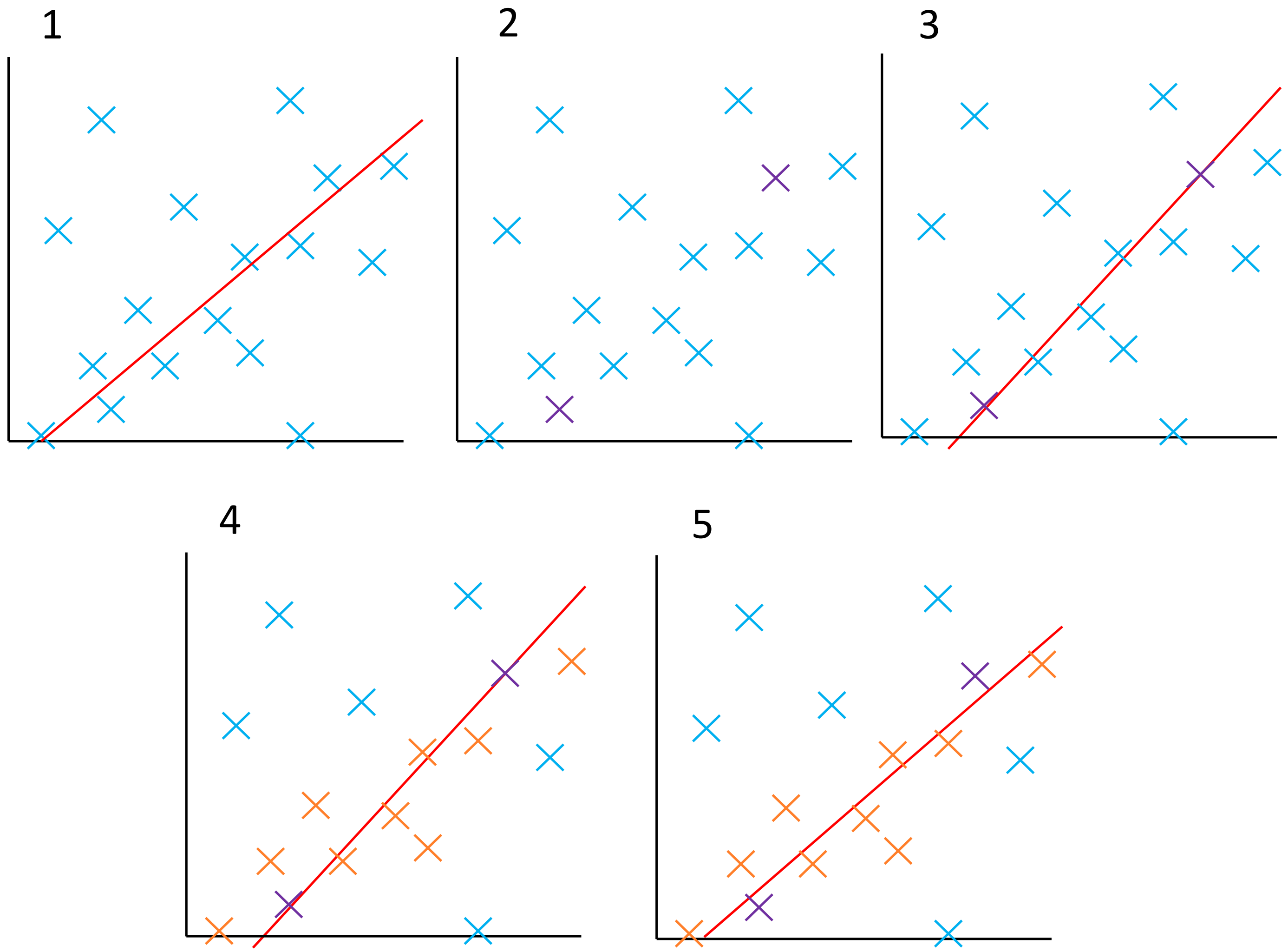
1. Randomly sample the minimum amount of points for method

2. Find parameters of model based solely on those points

3. Find all points consistent with that model

4. If proportion of inliers is higher than some threshold, re-estimate model with all inliers. Otherwise go back to step 1

5. If error metric is low enough, halt OR keep going for set number of iterations and keep best parameters



Essential Matrix

Essential Matrix is E such that

$\hat{x}_1^T E \hat{x}_2 = 0.$

For $\hat{x}_j = K^{-1} x_j$ with calibration matrix K and image coordinates x_j.

A real non-zero 3×3 matrix E is an Essential Matrix if and only if it satisfies

$EE^T E - \frac{1}{2} trace(EE^T)E = 0$

Recovering pose

SVD: $E \sim U\, diag(1,1,0) V^T$

$$t \sim t_u \equiv [u_{13} \quad u_{23} \quad u_{33}]^T$$

$R_a \equiv UDV^T \qquad R_b \equiv UD^T V^T$

$$D = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Four possible poses, find which using cheirality constraint.

Additional constraints are imposed by each point correspondence $\tilde{q}^T \tilde{E} = 0$, where

$$\tilde{q} \equiv [q_1 q_1' \quad q_2 q_1' \quad q_3 q_1' \quad q_1 q_2' \quad q_2 q_2' \quad q_3 q_2' \quad q_1 q_3' \quad q_2 q_3' \quad q_3 q_3']^T$$
$$\tilde{E} \equiv [E_{11} \quad E_{12} \quad E_{13} \quad E_{21} \quad E_{22} \quad E_{23} \quad E_{31} \quad E_{32} \quad E_{33}]^T$$

Stack the $\tilde{q}^T$ for the five points, get four matrices which span the right null space of this matrix, $\tilde{X}, \tilde{Y}, \tilde{Z}, \tilde{W}$. Then $E = xX + yY + zZ + wW$ for some scalars x, y, z, w. Set $w = 1$ and solve using $\tilde{q}^T \tilde{E} = 0$

Kabsch

Two point clouds: X, Y

Centroid: average over all of the points $x_c = \frac{1}{N}\sum_{i=1}^{N} x_i$

To find rotation, want to minimize $E = \frac{1}{2N}\sum_{i=1}^{N}|x_i' - y_i|^2$ for $Rx = x'$

SVD: $XY^T \sim VSW^T$

Optimal rotation is given by $R = WV^T$.

This is not necessarily a proper rotation, so we impose $\det R = 1$ by instead setting

$$R = W\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & d\end{bmatrix}V^T \quad \text{with } d = \det WV^T$$

EPnP

Represents reference points p_i in terms of four "control points" c_i

$$^{W}p_i = \sum_{j=1}^{4} \alpha_{ij} \; ^{W}c_j, \; ^{C}p_i = \sum_{j=1}^{4} \alpha_{ij} \; ^{C}c_j$$

$$w_i \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} = \begin{bmatrix} f_u & 0 & u_c \\ 0 & f_c & v_c \\ 0 & 0 & 1 \end{bmatrix} \sum_{j=1}^{4} \alpha_{ij} \begin{bmatrix} ^{C}x_j \\ ^{C}y_j \\ ^{C}z_j \end{bmatrix}$$

$$\sum_{j=1}^{4} \alpha_{ij} f_x \; ^{C}x_j + \alpha_{ij}(x_c - u_i)^{C}z_j = 0$$

$$\sum_{j=1}^{4} \alpha_{ij} f_y \; ^{C}y_j + \alpha_{ij}(x_c - u_i)^{C}z_j = 0$$

Linear system of the form $Mx = 0$, $x = \begin{bmatrix} ^{C}c_1^T \\ ^{C}c_2^T \\ ^{C}c_3^T \\ ^{C}c_4^T \end{bmatrix}$

The solution belongs to the kernel of M, and can be expressed as

$$x = \sum_{i=1}^{N} \beta_i v_i,$$

where v_i are the columns of the right singular vectors of M. The β_i are found using Gauss-Newton optimization.

Projective geometry

Camera model:

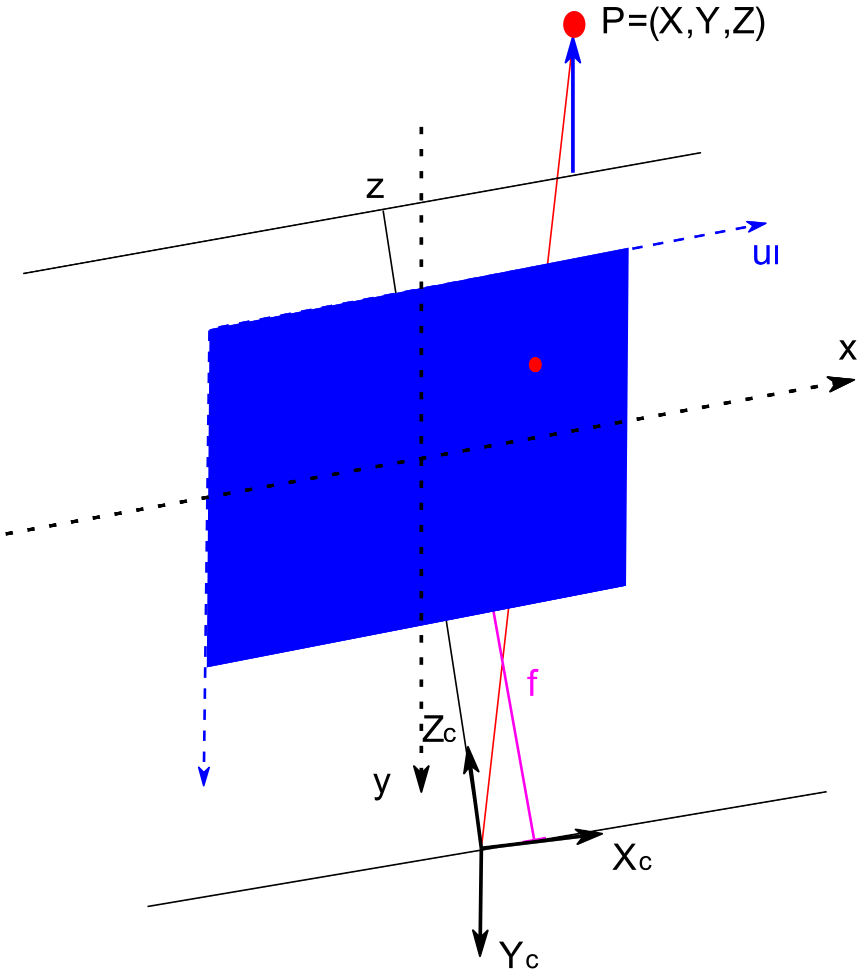
$$s\begin{bmatrix}u\\v\\1\end{bmatrix}=\begin{bmatrix}f_x & 0 & c_x\\0 & f_y & c_y\\0 & 0 & 1\end{bmatrix}\begin{bmatrix}r_{11} & r_{12} & r_{13} & t_1\\r_{21} & r_{22} & r_{23} & t_2\\r_{31} & r_{32} & r_{33} & t_3\end{bmatrix}\begin{bmatrix}X\\Y\\Z\\1\end{bmatrix}$$

Projection:

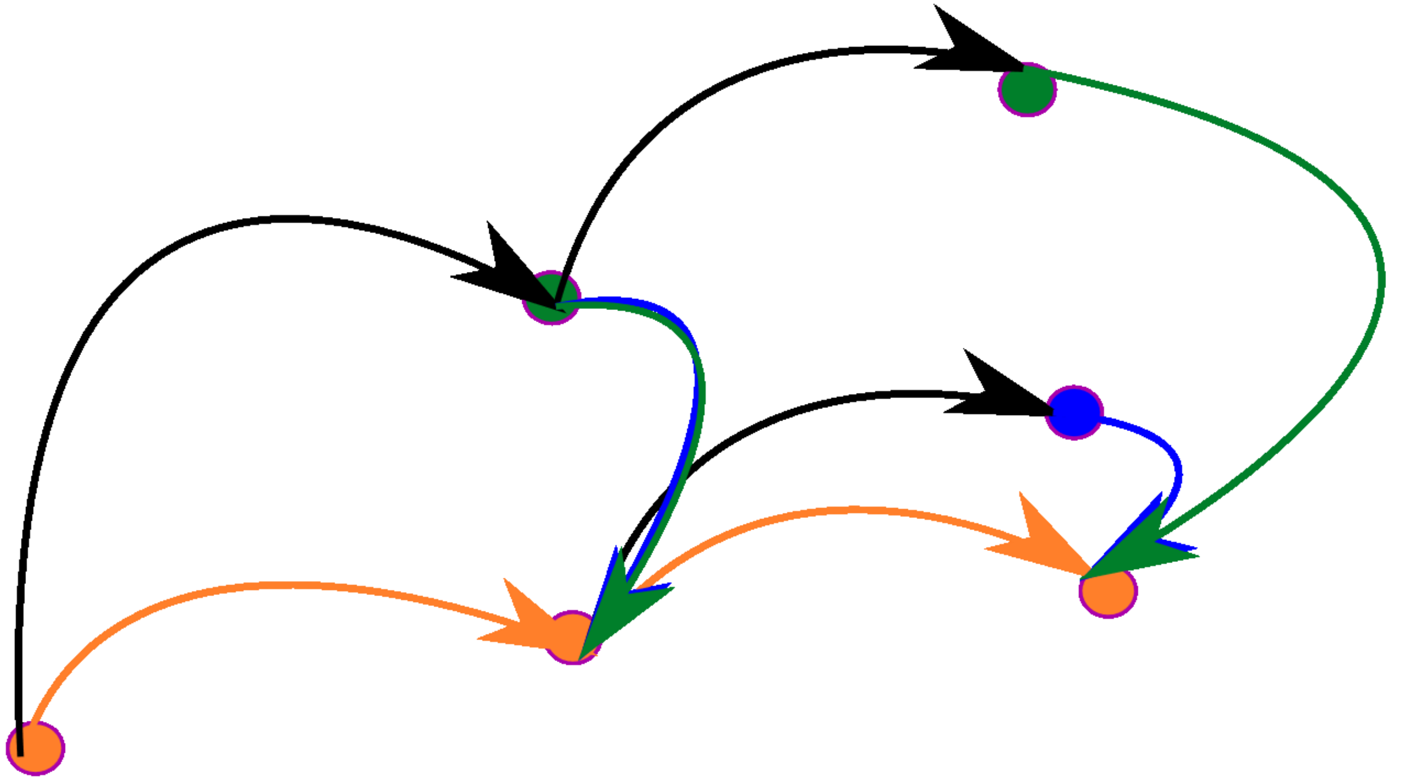
$$\pi({}^{I}p)=\left(\frac{s(u-c_x)}{f_x},\frac{s(v-c_y)}{f_y},s\right)$$

Reprojection:

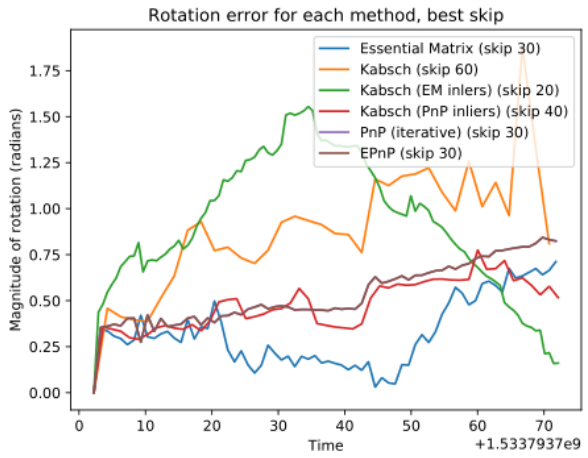
$$\pi^{-1}({}^{C}p)=\left(\frac{xf_x}{z}+c_x,\frac{yf_y}{z}+c_y\right)$$



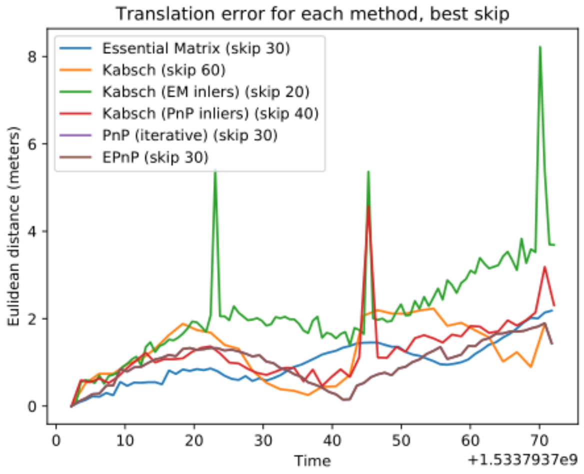
Relative and absolute errors



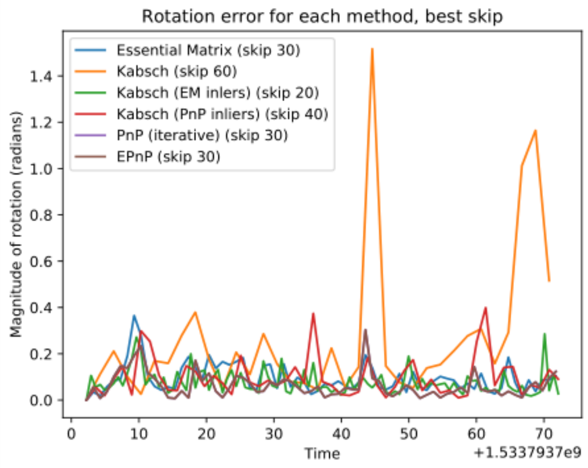
Results - errors



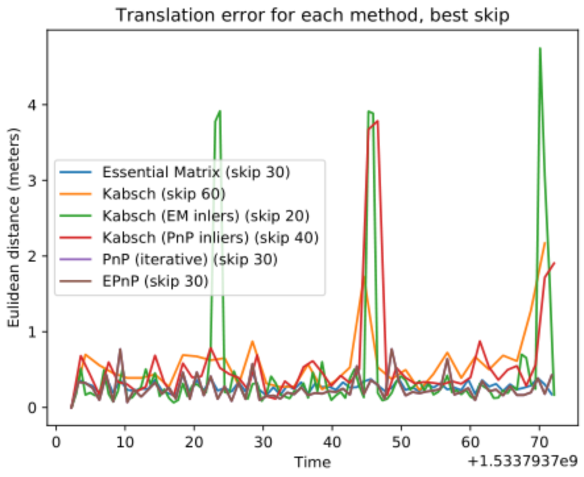
(a) Absolute rotation error



(b) Absolute translation error



(c) Relative rotation error



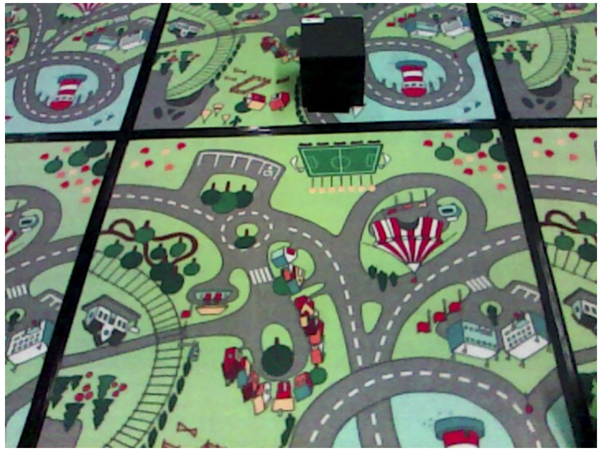
(d) Relative translation error

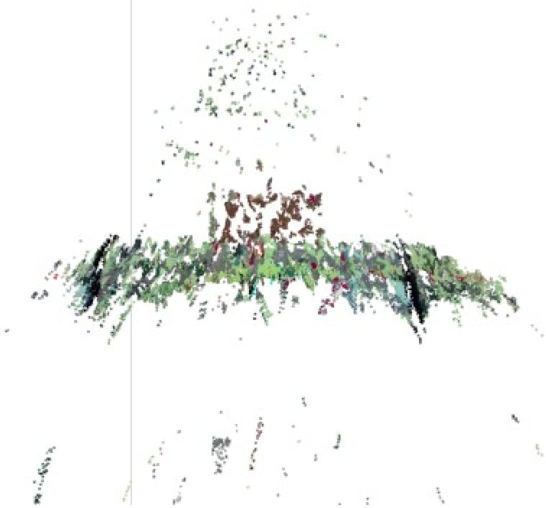
Method	Images skipped	Mean rotation (rad)	Standard deviation rotation	Mean translation (m)	Standard deviation translation
Essential Matrix	20	0.4894	0.1564	**0.1860**	0.0545
	30	**0.3210**	0.1866	0.2715	0.0768
	40	0.9839	0.5943	0.3231	0.0893
	50	0.4587	0.1806	0.3986	0.0978
	60	0.7676	0.2862	0.5786	0.1229
	70	0.4189	0.1678	0.3671	0.0912
	80	1.1206	0.2977	0.4390	0.1082
	90	1.2945	0.6580	0.4803	0.1184
Kabsch	20	1.0833	0.4862	0.5733	0.8449
	30	1.3750	1.1153	0.6569	0.7853
	40	1.6761	0.9486	0.6968	0.9587
	50	1.0069	0.2896	0.5875	0.6919
	60	0.8842	0.3332	0.5836	0.4071
	70	1.6081	0.7557	**0.5121**	0.2411
	80	1.4819	1.0692	0.9134	1.1902
	90	**0.7386**	0.4512	0.9596	0.8742
PnP (iterative)	20	0.6246	0.1879	**0.1654**	0.1000
	30	0.5321	0.1672	0.2498	0.1534
	40	0.7845	0.2815	0.3059	0.1689
	50	0.7922	0.2451	0.3926	0.2385
	60	0.9364	0.3424	0.4287	0.1390
	70	**0.3606**	0.0971	0.5367	0.3136
	80	1.1450	0.9139	0.5945	0.2970
	90	1.5099	0.9690	1.0761	0.9652

Results – computational time

Method	Images skipped	Computational time (s)				
		Finding features	Finding 3D	Method	Total	Average
Essential Matrix	30	20.53407407	0	8.06119919	28.59527326	0.40850390
Kabsch	60	8.56764126	1.13109493	1.42120957	11.11994576	0.31771274
Kabsch (EM inliers)	20	24.2366011	2.82343698	0.0179517269	27.07798982	0.25788562
Kabsch (PnP inliers)	40	15.5132024	2.13250232	0.0120806694	17.65778542	0.33957280
PnP (iterative)	30	20.56354165	0.62145519	138.94879413	160.13379097	2.28762559
EPnP	30	20.57645249	0.60471034	138.74758315	159.92874599	2.28469637

Box investigation

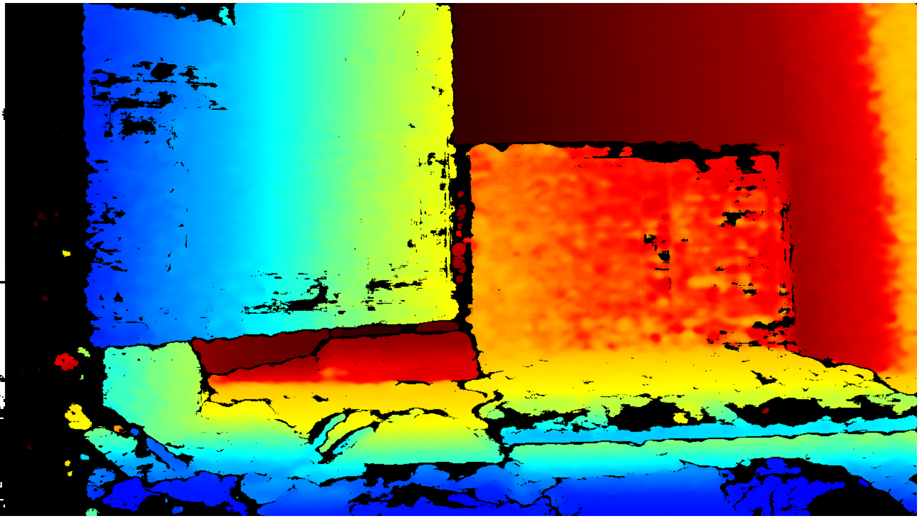




R200 vs D415

First R200

Second R200



D415