Efficient and Robust Circle Grids for Fiducial Detection

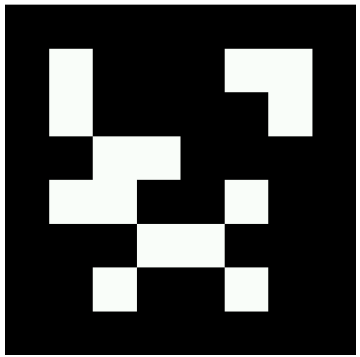
Master's Colloquium

Michael Loipführer

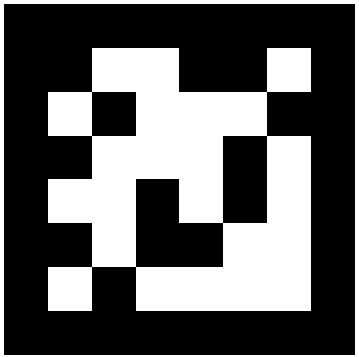
Department of Informatics

May 23, 2022

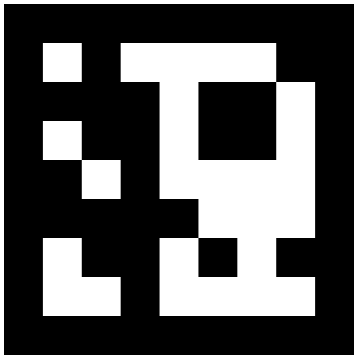
What are fiducial markers?



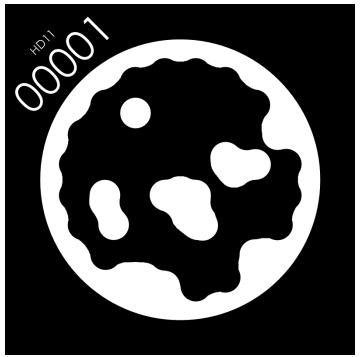
ARToolkitPlus [1]



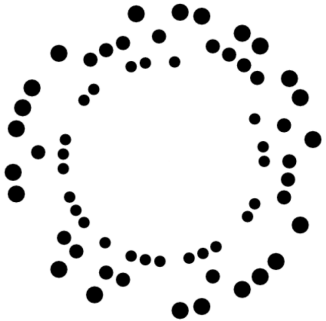
AprilTag [2], [3]



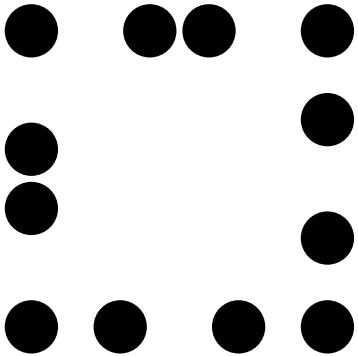
ArUco [4]



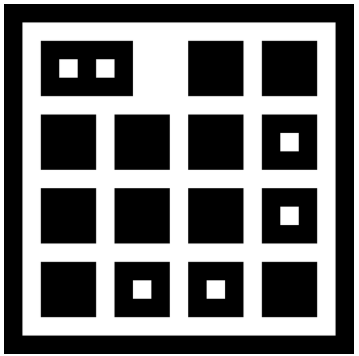
STag [5]



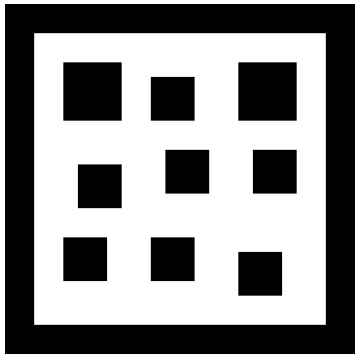
RuneTag [6]



Pi-Tag [7]

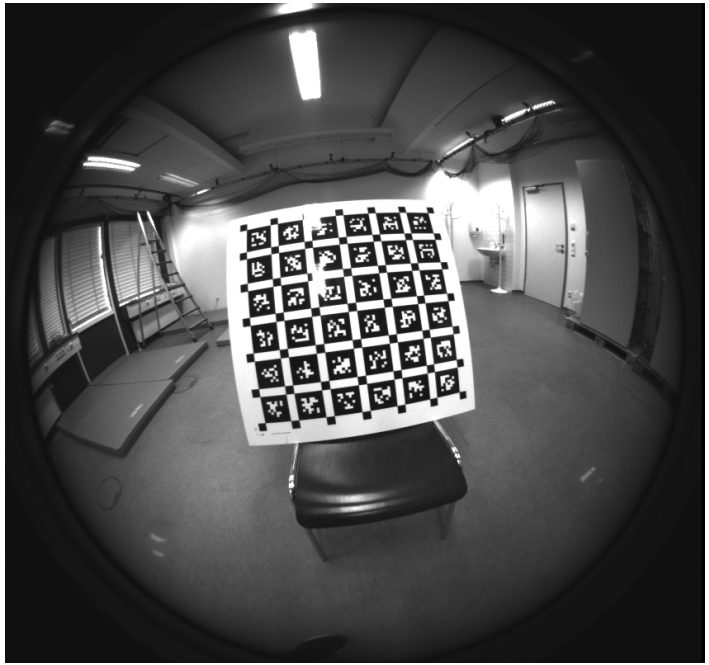


TopoTag [8]



LFTag [9]

What are fiducial markers?



Camera Calibration

Robotic Applications[1]

Augmented Reality[2]

[1] *AprilTag website*. URL: https://april.eecs.umich.edu/software/apriltag (visited on 05/16/2022).

[2] *Researchgate*. URL: https://www.researchgate.net/figure/Circular-marker-for-Augmented-Reality_fig1_259752709 (visited on 05/21/2022).

What are fiducial markers?

Designed for

- robust detections
- stable 3D pose recovery
- unique marker identifiers

Motivation

Existing methods do not work well in very distorted images

Motivation

Existing methods do not work well in very distorted images

Goals of this Thesis

Design a novel fiducial marker system based on circle grids that specifically

- provides robust detections
- achieves stable pose recovery
- works well with distorted fisheye cameras
- can be composed into larger marker grids

Outline

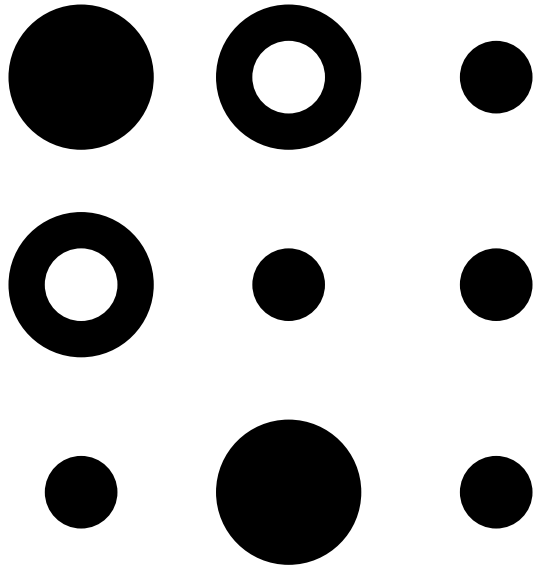
Marker Design

Circles

- robust detections even with high distortion
- subpixel accuracy

3×3 Grid

- compact layout
- regular geometry helps detection scheme

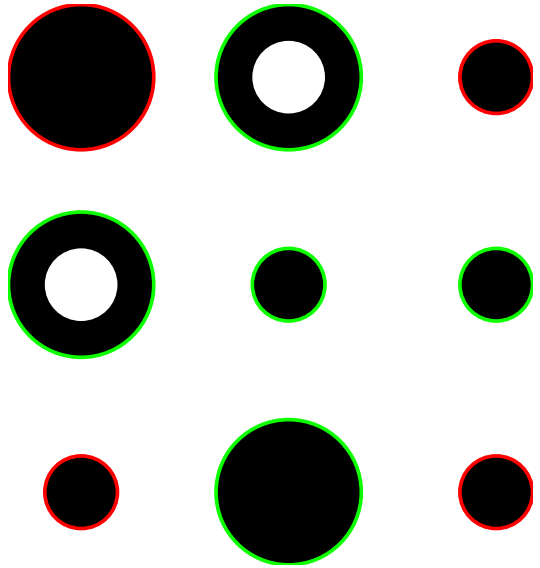


Example Marker

Marker Design

Marker Payload

- recover the orientation of a tag
- discard erroneous detections



Corners: 0111, Full payload: 021110121

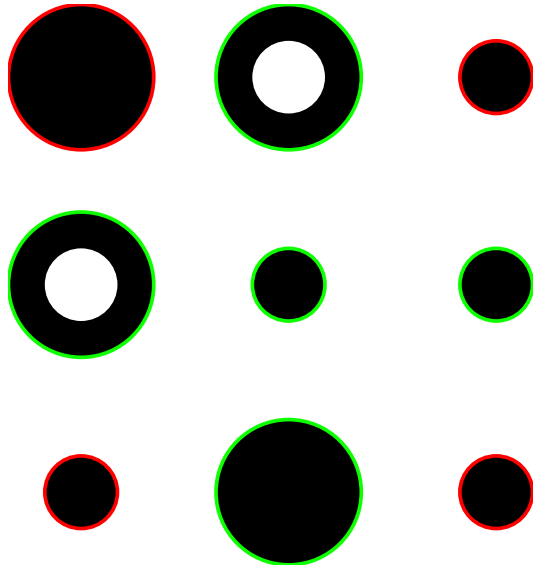
Marker Design

Marker Payload

- recover the orientation of a tag
- discard erroneous detections

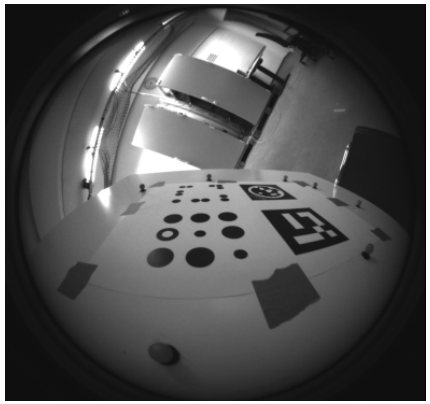
Coding Scheme

- Lyndon words for rotational uniqueness in corners
- remaining 5 digits for arbitrary error detection



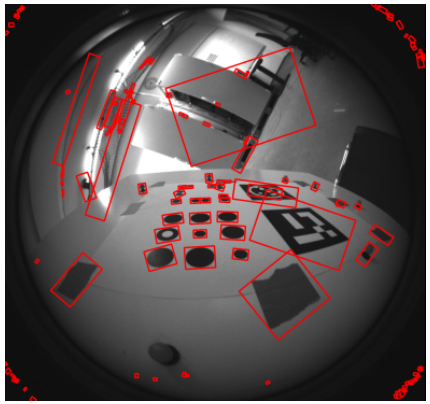
Corners: 0111, Full payload: 021110121

Detection Pipeline

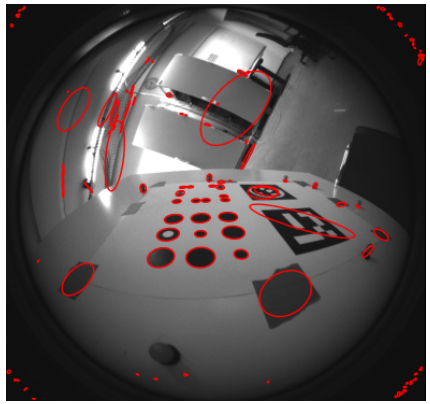


Original image

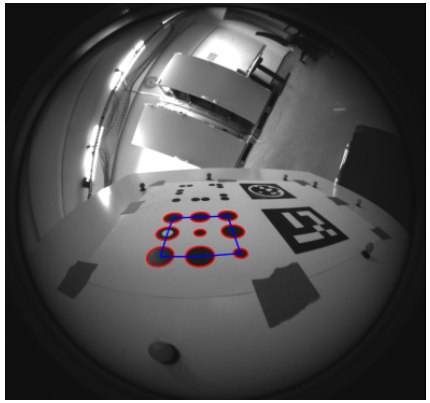
Thresholded image



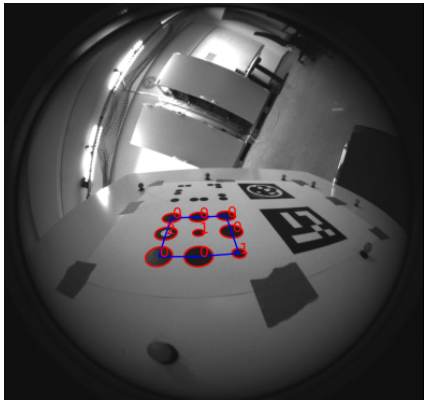
Ellipse candidates



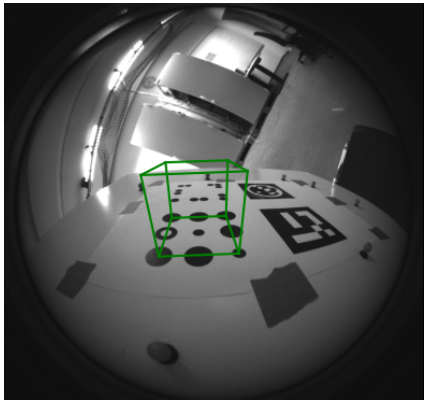
Detected ellipses



Marker candidates

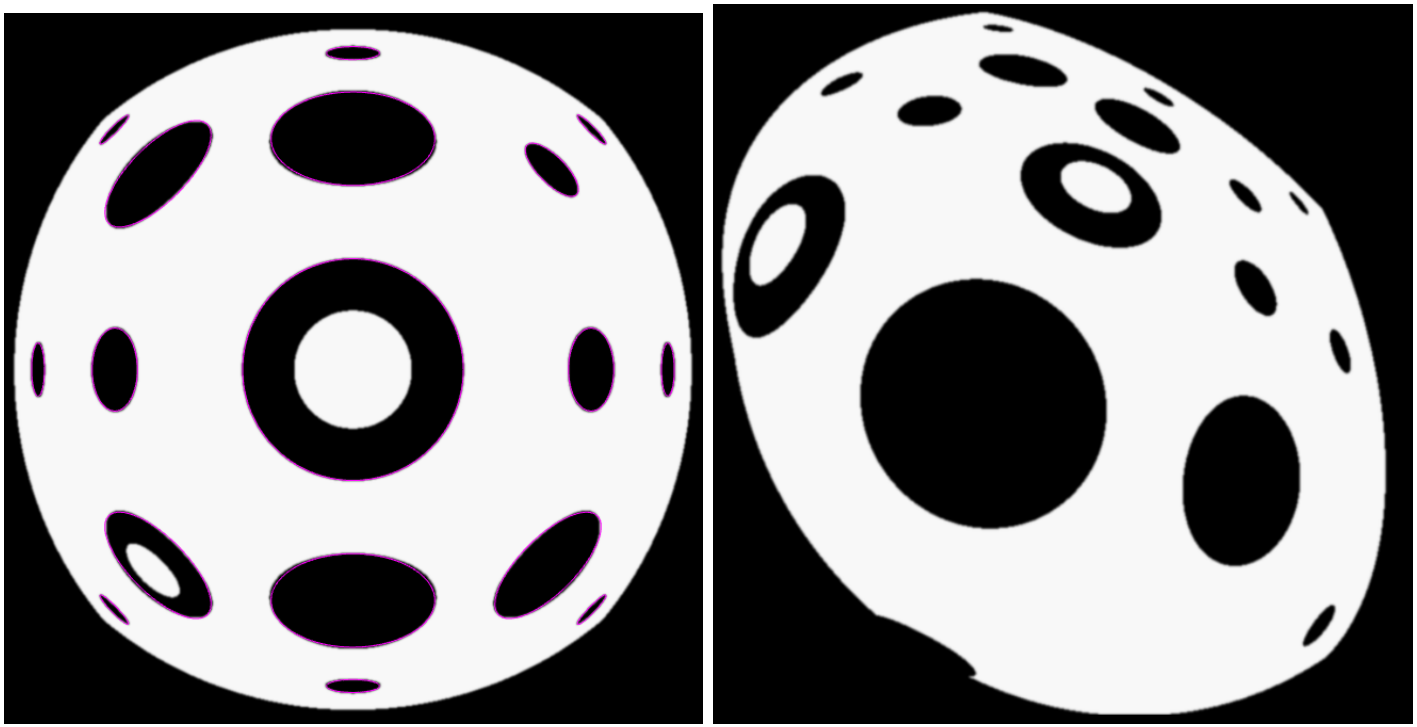


Valid markers



Pose Estimation

Marker Candidate Generation



Marker Candidate Generation

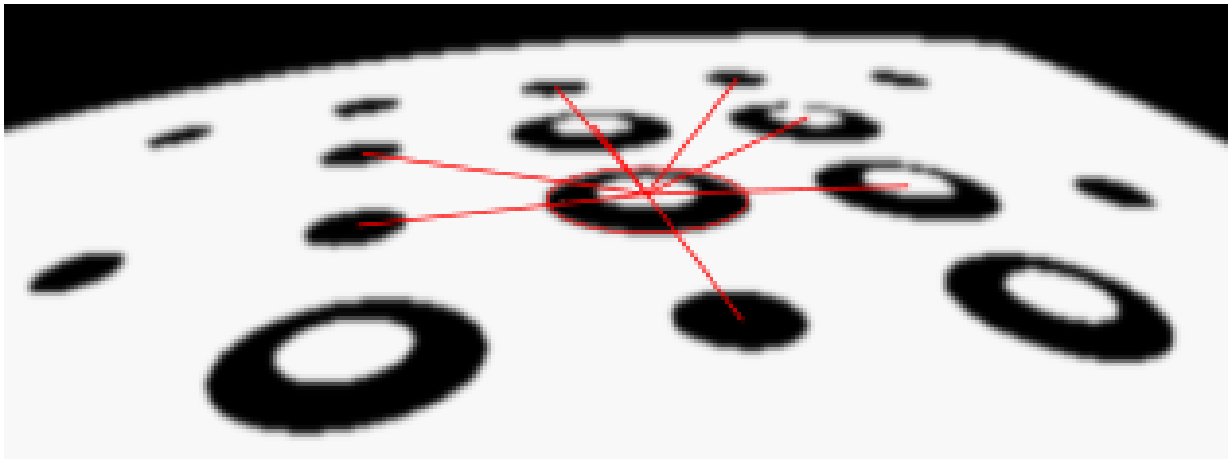
Basic Idea

- perform a KNN-search for every ellipse
- check if the 8 nearest neighbors fit a 3×3 grid

Marker Candidate Generation

Basic Idea

- perform a KNN-search for every ellipse
- check if the 8 nearest neighbors fit a 3×3 grid
- KNN-search with $k \geq 8$
- geometric heuristics based on angles and distances between ellipses to filter out invalid marker geometries



Payload Decoding

Ellipse Type Decoding

- relate relative distances between ellipses with measured sizes
- compare to known true sizes of different ellipse types

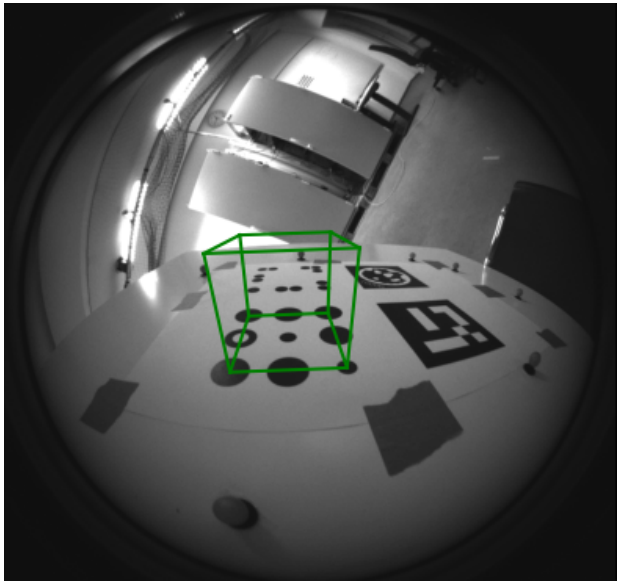
Payload Check

- recovery of rotation using payload of corner points
- validity check of any error detection schemes

Pose Estimation

Method

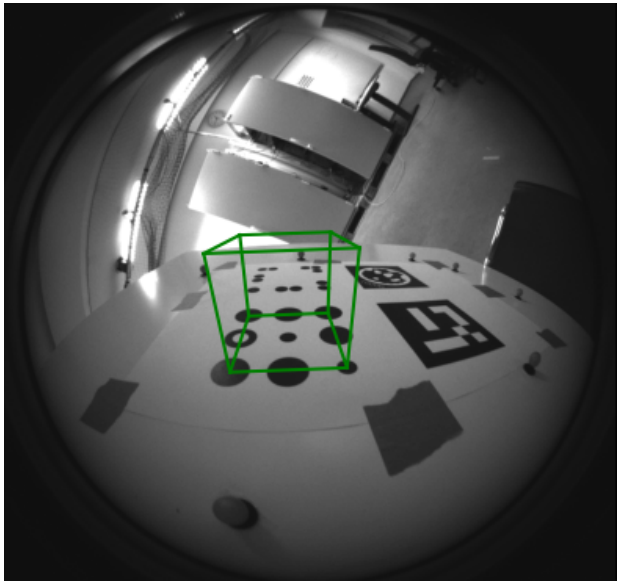
- all 9 ellipses used as 2D - 3D point correspondences
- UPNP [12] and KNEIP [13] used as initializations
- non-linear optimization for pose refinement



Pose Estimation

Method

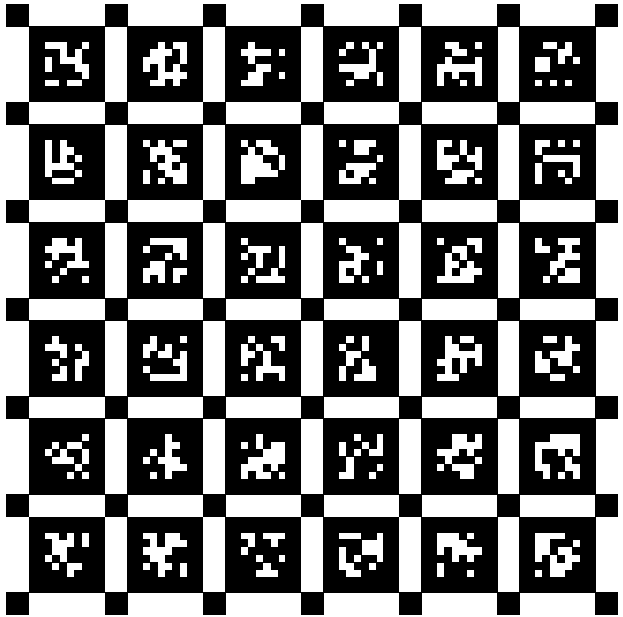
- all 9 ellipses used as 2D - 3D point correspondences
- UPNP [12] and KNEIP [13] used as initializations
- non-linear optimization for pose refinement



Benefits of our method

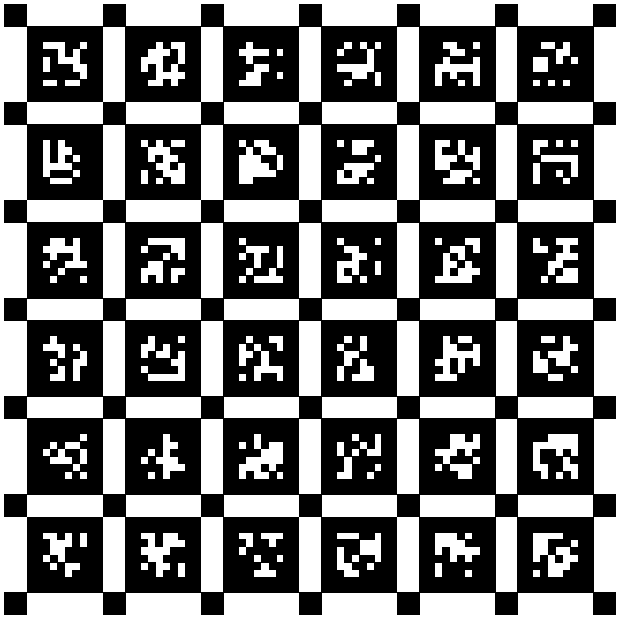
- ellipse detection produces accurate 2D feature points
- more correspondences leads to more stable poses

Composable Marker Grids

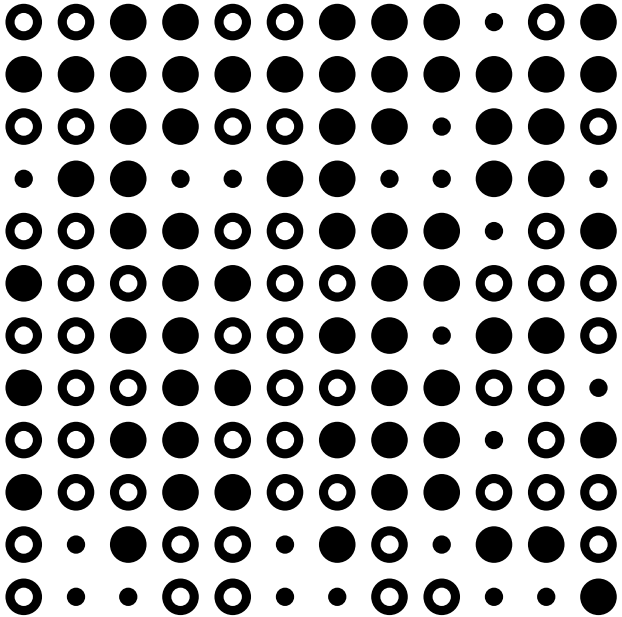


AprilGrid

Composable Marker Grids



AprilGrid



Ours

Composable Marker Grids

Camera Calibration

- good performance for fisheye cameras
- more robust to detection errors than AprilGrid

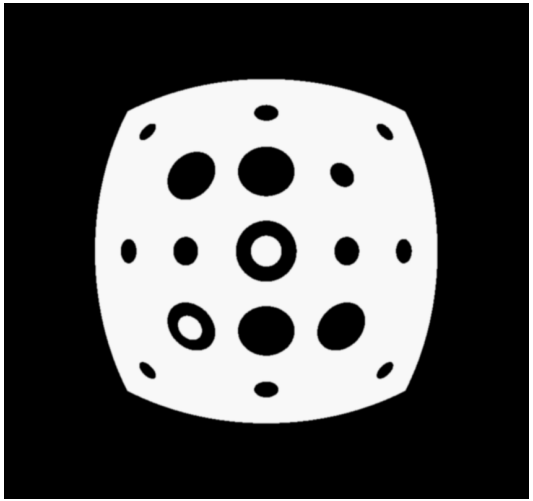
Grids as Fiducials

- large number of unique marker identifiers
- more options for error detection and correction

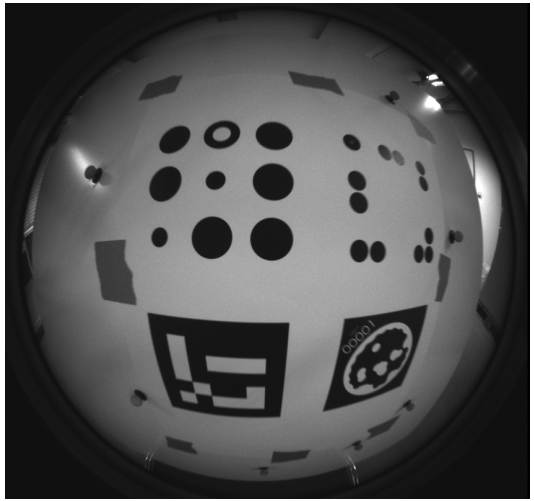
Evaluation

Evaluation of

- detection precision and recall
- pose estimation accuracy
- in real world and simulated images

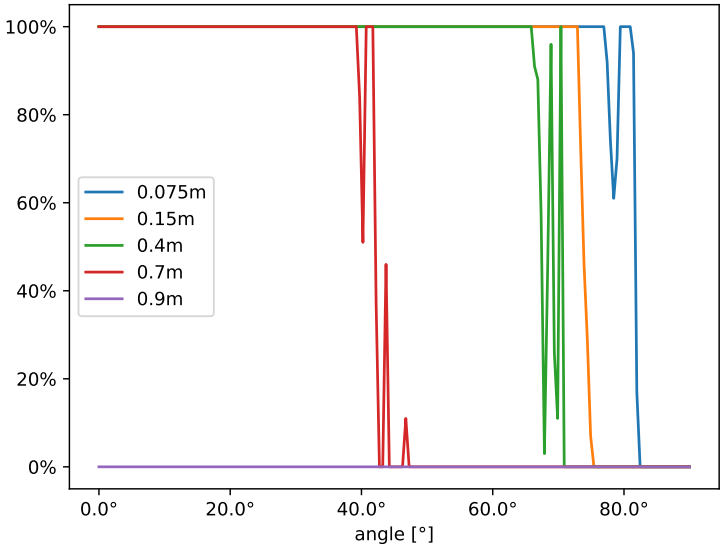


Simulation

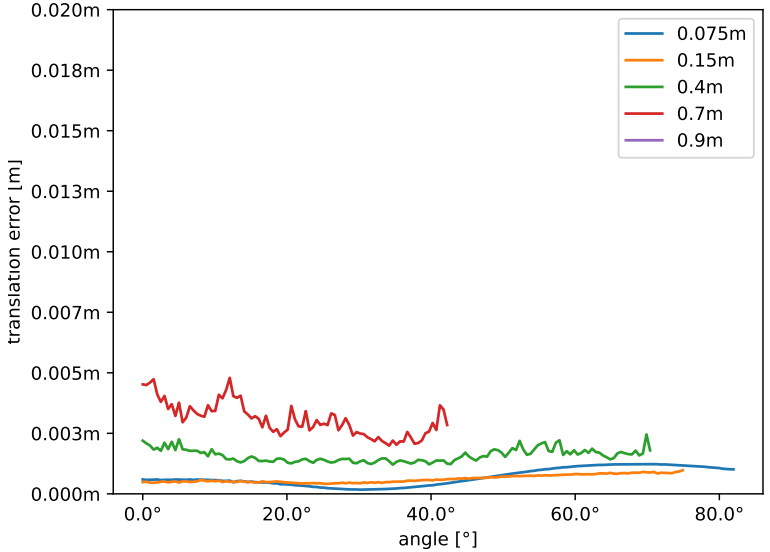


Real World

Evaluation - Simulated Data



Detection Recall



Pose Translation Error

Evaluation - Real World Data

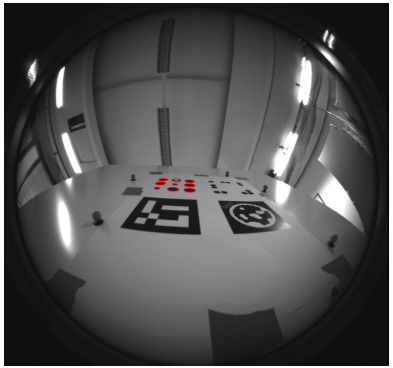
Marker System	distance	low angle close	pan tilt close	mixed	planar close
ArUco	**56.35%**	**83.37%**	55.65%	**89.78%**	54.88%
STag	37.88%	63.00%	60.58%	86.69%	62.80%
Pi-Tag	10.38%	39.87%	7.68%	0.00%	0.26%
Ours	39.04%	82.34%	**71.01%**	88.11%	**66.23%**

Detection Recall

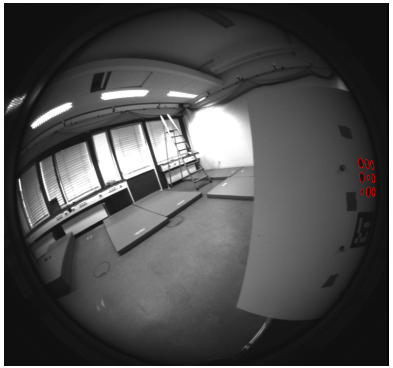
Marker System	distance	low angle close	pan tilt close	mixed	planar close
ArUco	0.3334	0.0077	0.0458	0.2227	0.0236
STag	0.1969	0.1013	0.0850	0.1319	0.1204
Pi-Tag	0.0900	0.0212	0.0229	nan	nan
Ours	**0.0468**	**0.0024**	**0.0044**	**0.0325**	**0.0051**

Root Mean Translation Error

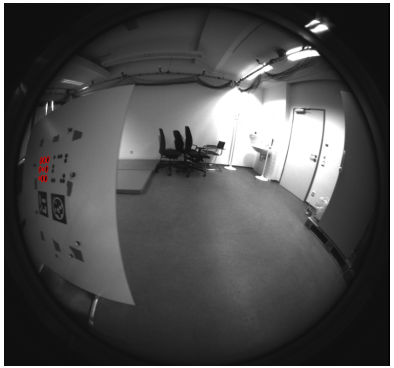
Evaluation - Qualitative Results



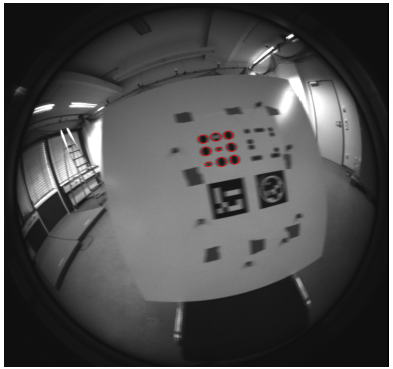
Low viewing angle



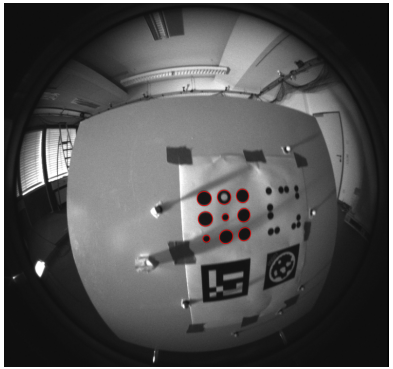
Large image distortion



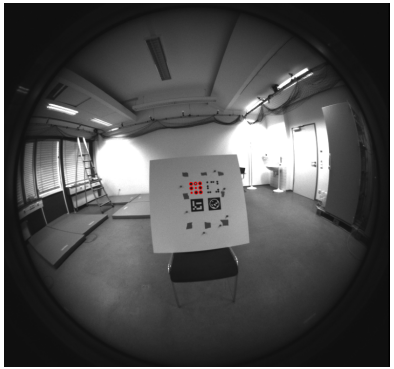
Large image distortion



Significant motion blur



Difficult lighting



Large viewing distance

Evaluation - Failure Cases

Marker System	LabelMe	Indoor Scene Recognition
ArUco	**110 (3.77%)**	**193 (1.24%)**
STag	293 (10.03%)	308 (1.97%)
Ours	2672 (91.51%)	3146 (20.15%)

False positive detections on the LabelMe [14] and indoor scene recognition [15] datasets.

Examples of false positive detections.

Live Demo

3

[3] *Pinclipart website*. URL: https://www.pinclipart.com/pindetail/TiTRbw_request-demo-live-demo-clipart-png-download/ (visited on 09/08/2019).

Questions?

References I

[1] D. Wagner and D. Schmalstieg. “Artoolkitplus for pose tracking on mobile devices”. In: (2007).

[2] J. Wang and E. Olson. “AprilTag 2: Efficient and robust fiducial detection”. In: *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Oct. 2016.

[3] J. Wang and E. Olson. “AprilTag 2: Efficient and robust fiducial detection”. In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2016, pp. 4193–4198.

[4] F. J. Romero-Ramirez, R. Muñoz-Salinas, and R. Medina-Carnicer. “Speeded up detection of squared fiducial markers”. In: *Image and Vision Computing* 76 (2018), pp. 38–47.

[5] B. Benligiray, C. Topal, and C. Akinlar. “STag: A stable fiducial marker system”. In: *Image and Vision Computing* 89 (2019), pp. 158–169.

[6] F. Bergamasco, A. Albarelli, E. Rodolà, and A. Torsello. “RUNE-Tag: A high accuracy fiducial marker with strong occlusion resilience”. In: *CVPR 2011*. 2011, pp. 113–120.

[7] F. Bergamasco, A. Albarelli, and A. Torsello. “Pi-Tag: A fast image-space marker design based on projective invariants”. In: *Machine Vision and Applications* 24 (Aug. 2013).

[8] G. Yu, Y. Hu, and J. Dai. “TopoTag: A Robust and Scalable Topological Fiducial Marker System”. In: *IEEE Transactions on Visualization and Computer Graphics (TVCG)* 27.9 (2021), pp. 3769–3780.

References II

[9] B. Wang. “LFTag: A Scalable Visual Fiducial System with Low Spatial Frequency”. In: *2020 2nd International Conference on Advances in Computer Technology, Information Science and Communications (CTISC)*. 2020, pp. 140–147.

[10] *AprilTag website*. URL: https://april.eecs.umich.edu/software/apriltag (visited on 05/16/2022).

[11] *Researchgate*. URL: https://www.researchgate.net/figure/Circular-marker-for-Augmented-Reality_fig1_259752709 (visited on 05/21/2022).

[12] L. Kneip, H. Li, and Y. Seo. “Upnp: An optimal o (n) solution to the absolute pose problem with universal applicability”. In: *European Conference on Computer Vision*. Springer. 2014, pp. 127–142.

[13] L. Kneip, D. Scaramuzza, and R. Siegwart. “A novel parametrization of the perspective-three-point problem for a direct computation of absolute camera position and orientation”. In: *CVPR 2011*. IEEE. 2011, pp. 2969–2976.

[14] B. C. Russell, A. Torralba, K. P. Murphy, and W. T. Freeman. “LabelMe: a database and web-based tool for image annotation”. In: *International journal of computer vision* 77.1 (2008), pp. 157–173.

[15] A. Quattoni and A. Torralba. “Recognizing indoor scenes”. In: *2009 IEEE conference on computer vision and pattern recognition*. IEEE. 2009, pp. 413–420.

References III

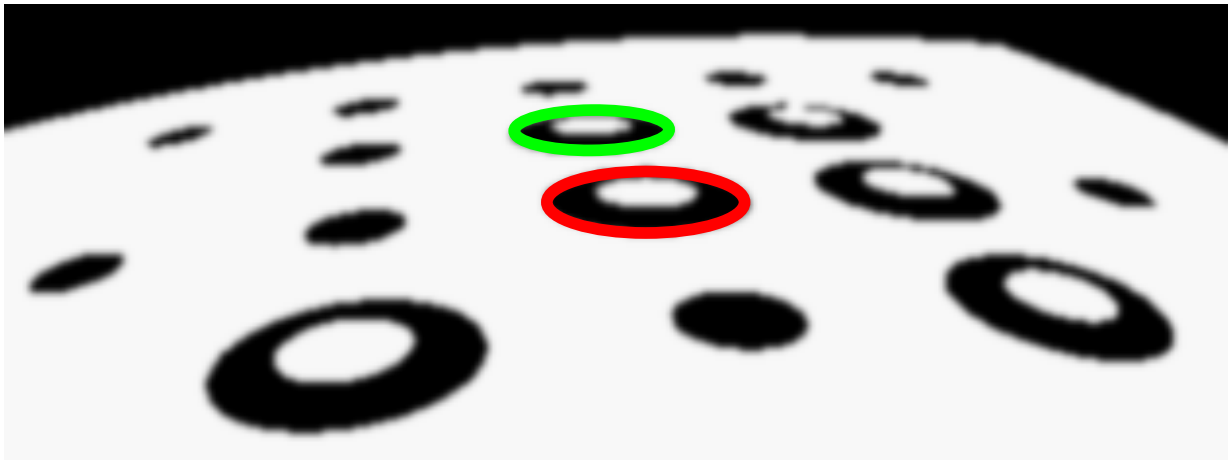
[16] *Pinclipart website*. URL: https://www.pinclipart.com/pindetail/TiTRbw_request-demo-live-demo-clipart-png-download/ (visited on 09/08/2019).

Backup Slides

Marker Candidate Generation

Geometric Heuristic

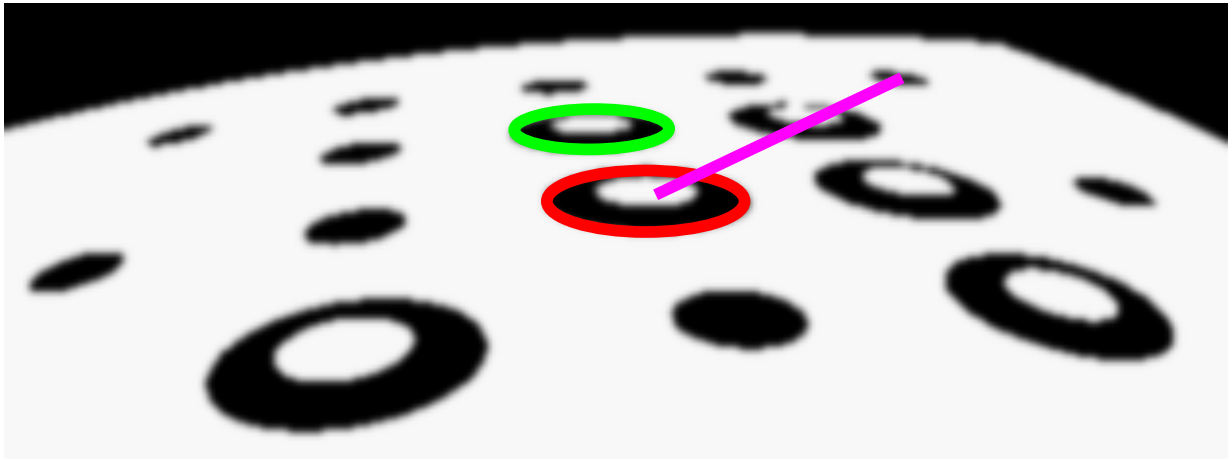
- find closest neighbor to center ellipse
- perform heuristic filtering based on angle to the closest neighbor



Marker Candidate Generation

Geometric Heuristic

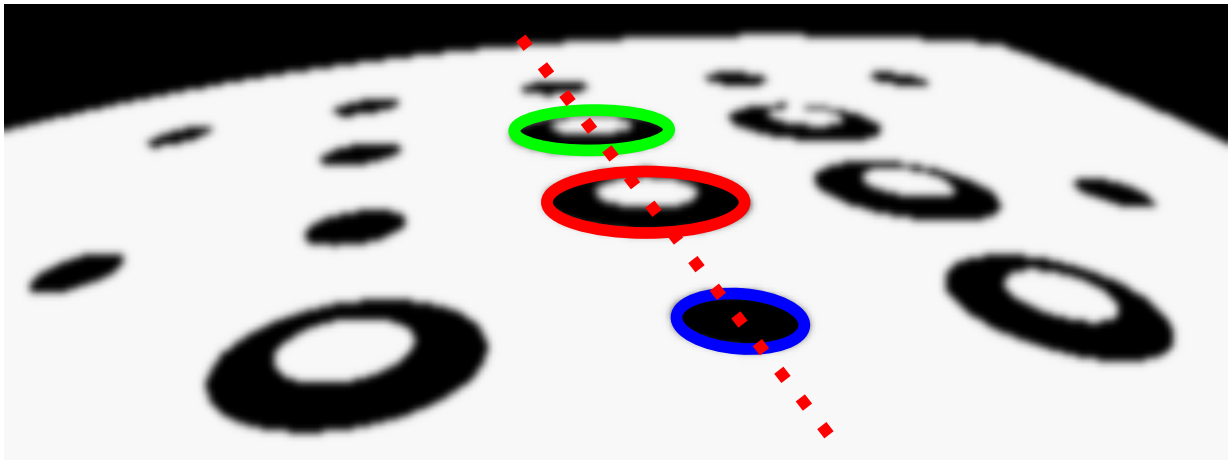
- find closest neighbor to center ellipse
- perform heuristic filtering based on angle to the closest neighbor



Marker Candidate Generation

Geometric Heuristic

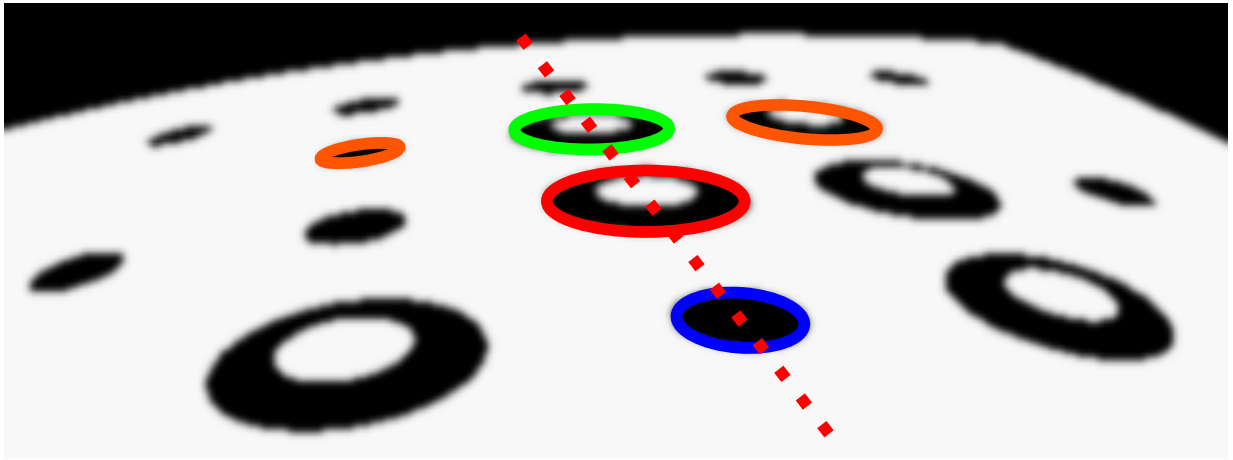
- find closest neighbor to center ellipse
- perform heuristic filtering based on angle to the closest neighbor



Marker Candidate Generation

Geometric Heuristic

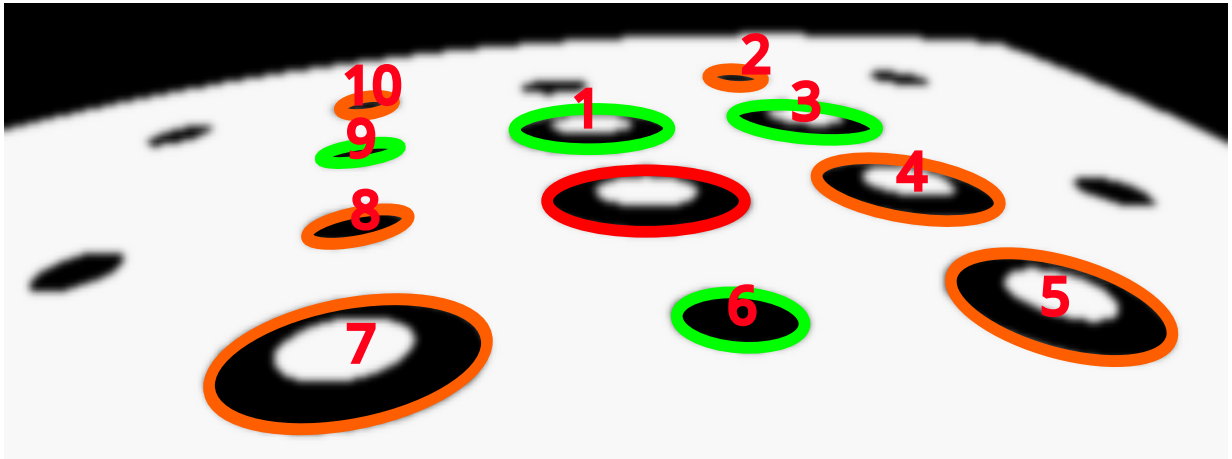
- find closest neighbor to center ellipse
- perform heuristic filtering based on angle to the closest neighbor



Marker Candidate Generation

Geometric Heuristic

- brute force search on the remaining neighboring ellipses for best alignment into 3 $\times$ 3 grid



Composable Marker Grids - Grid Generation

Grid size	Runtime	Number of grids
4×4	2.64s	262,144
5×5	213s	47,807,136
6×6	22h 50m	181,718,080
$\vdots$	?	≥ 1
19×19	?	≥ 1
20×20	-	0

Number of possible marker grids.