Autocalibration & 3D Reconstruction with Omnidirectional Cameras

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Central Omnidirectional Cameras

Catadioptric

Perspective cam.
Hyperbolic mirror
$360^\circ \times 186^\circ$

Orthographic cam.
Parabolic mirror
$360^\circ \times 210^\circ$

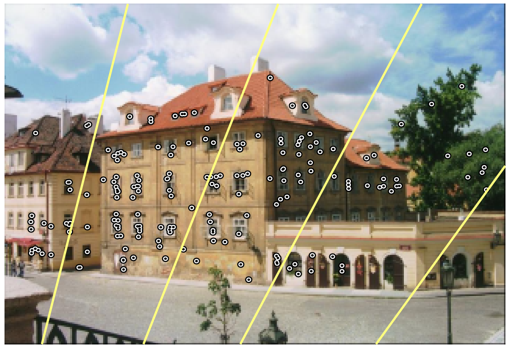
Dioptric

Nikon Coolpix
FC-E8 Lens
$360^\circ \times 183^\circ$

Canon EOS-1
Sigma Lens
$360^\circ \times 180^\circ$

Motivation

- Multiple view geometry of standard perspective cameras using point correspondences



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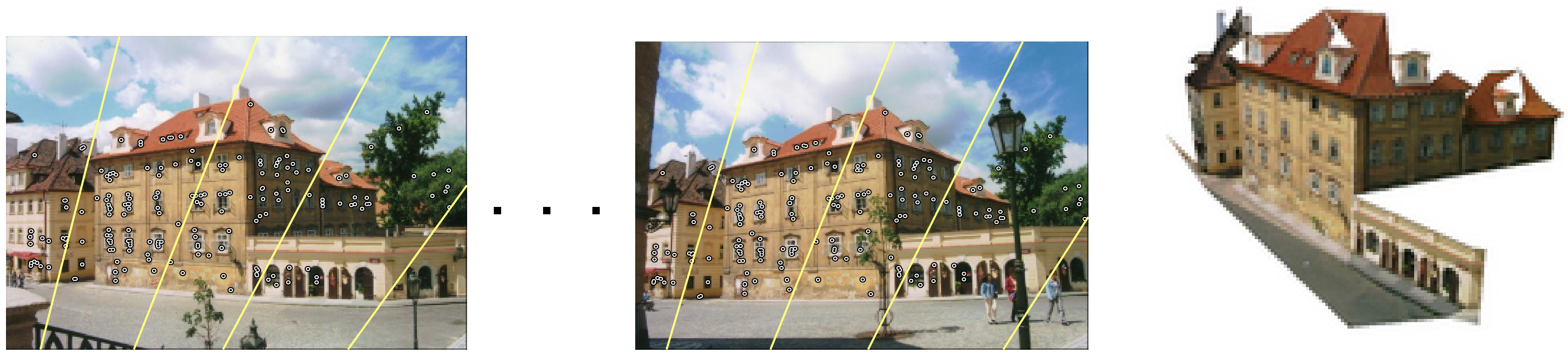
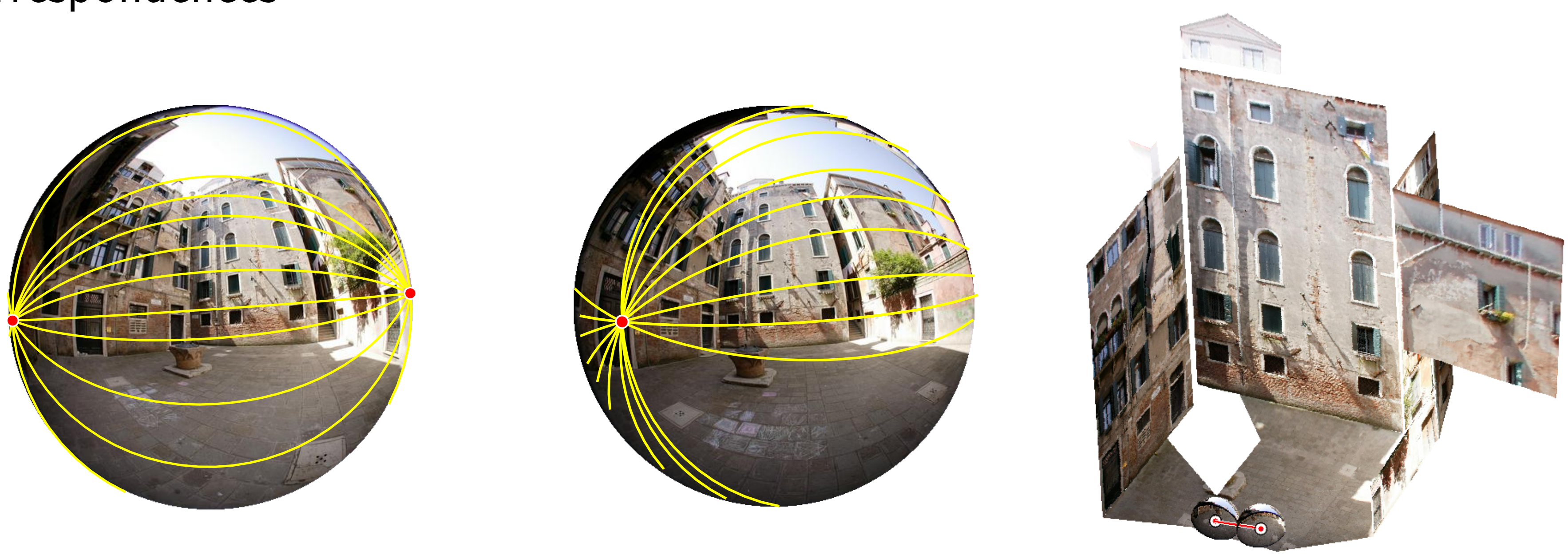


- Multiple view geometry of uncalibrated omnidirectional non-perspective cameras using point correspondences



Our contribution to the State-of-the-art

- Omnidirectional camera (dioptric & catadioptric) auto-calibration from epipolar geometry and tentative point correspondences

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- Solution for $\mathtt{F}$ and the camera model parameter a by solving the Polynomial Eigenvalue Problem

$$\left(\mathtt{D}_1 + a\mathtt{D}_2 + a^2\mathtt{D}_3 + \ldots\right)\mathbf{h} = \mathbf{0}$$

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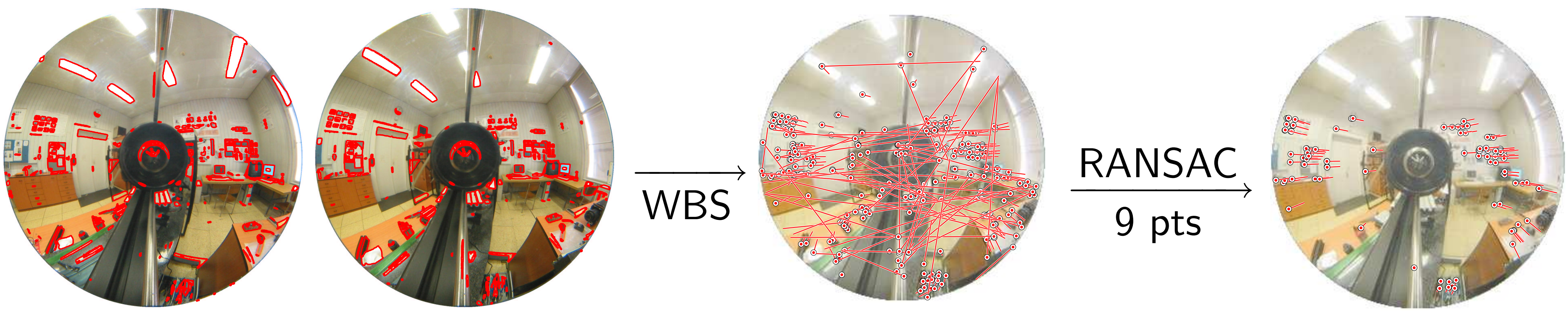
- RANSAC with 9-point (or 15-point) correspondences possible



(Matas et al BMVC 2002)

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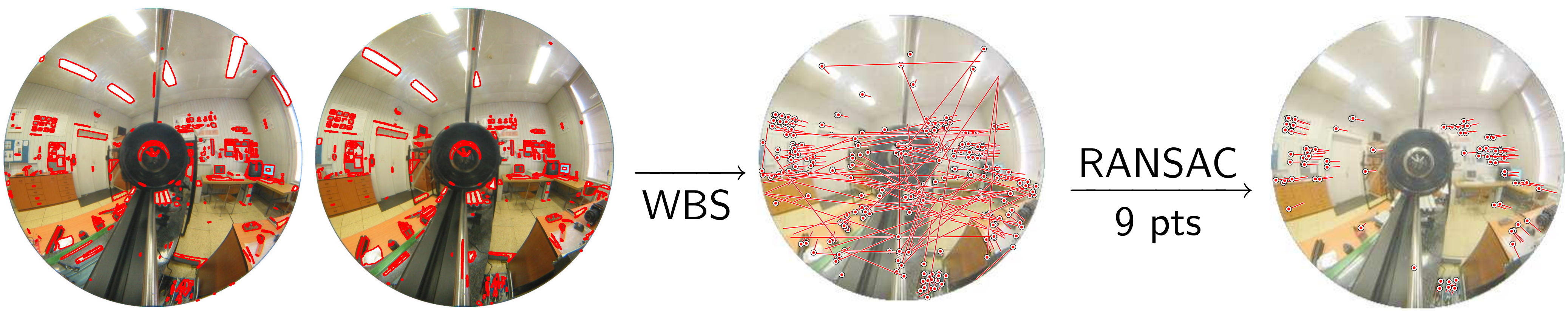

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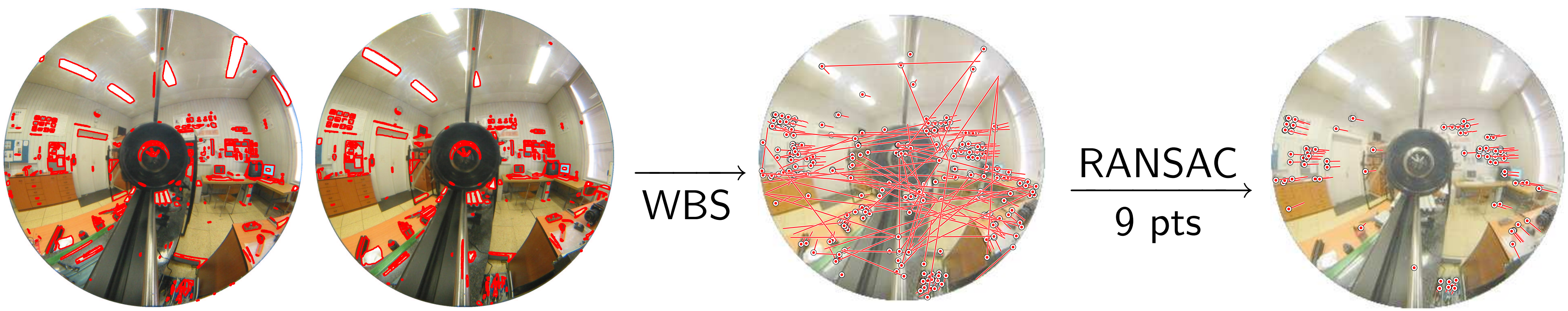

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- Previous works assumed lines or calibration objects in scene to calibrate the omnidirectional camera
- 3D metric reconstruction from uncalibrated central and slightly non-central omnidirectional images

Outline of the talk

1. Estimation of two view geometry of central dioptric & catadioptric omnidirectional cameras

2. Real non-central catadioptric omnidirectional cameras, their models, and stereo geometries

Part 1.

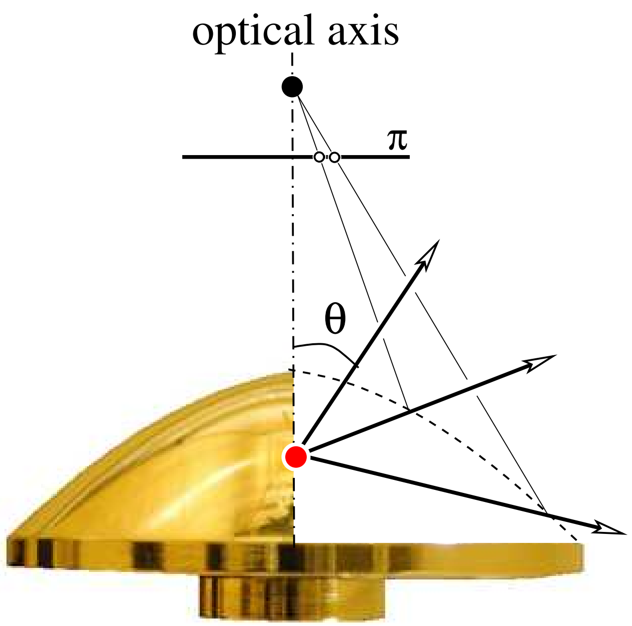
Estimation of two-view geometry of

central

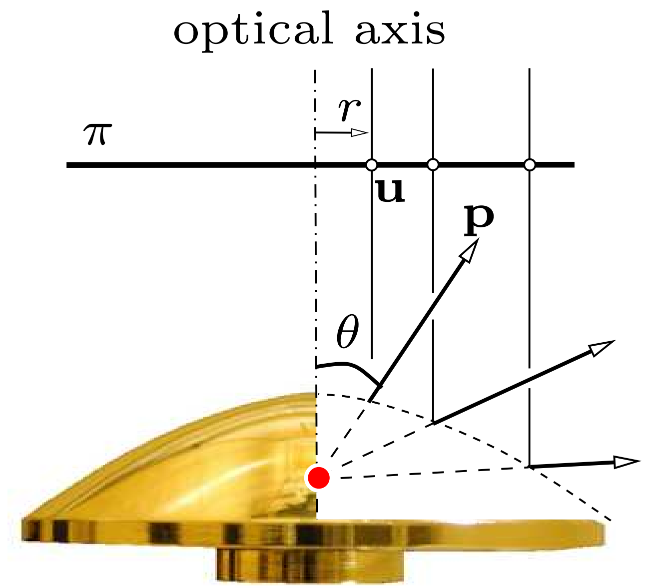
dioptric & catadioptric

omnidirectional cameras

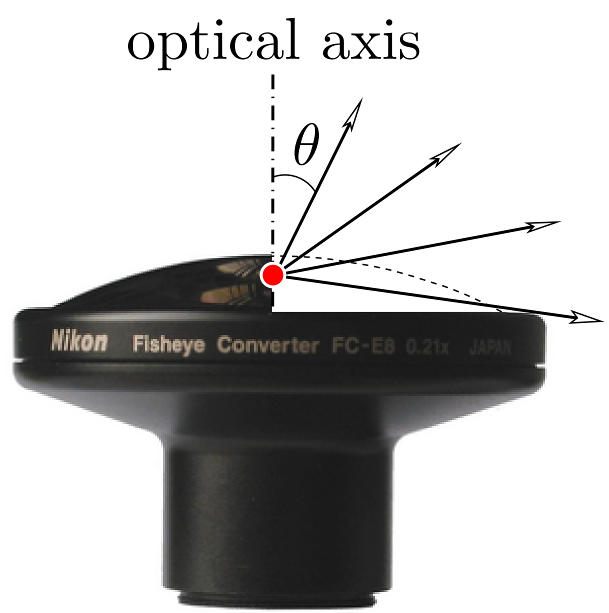
Central



Hyperbolic mirror
+ perspective camera

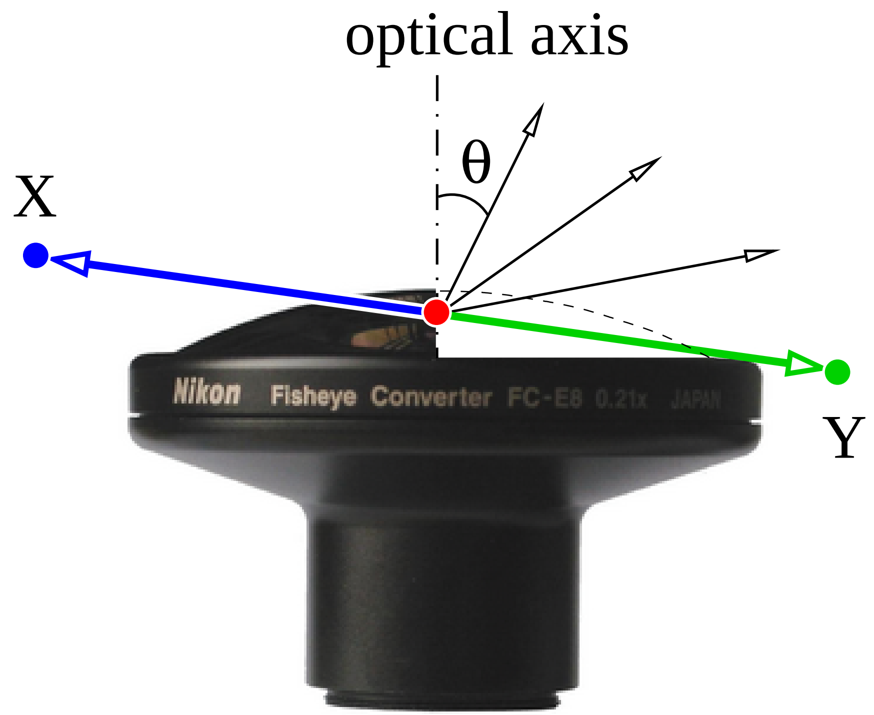


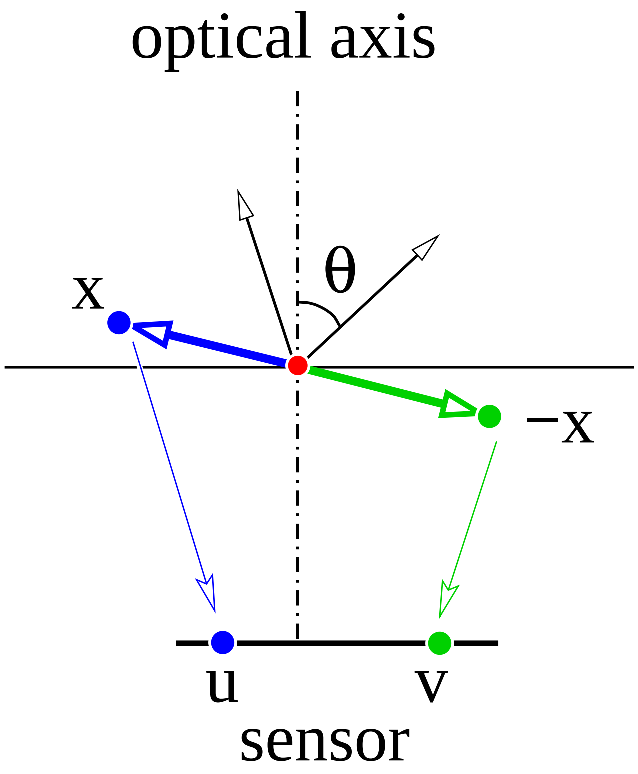
Parabolic mirror
+ orthographic camera



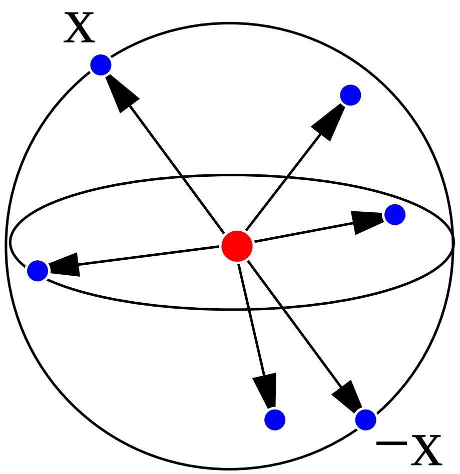
Fish-eye lens

Omnidirectional





Spherical Model



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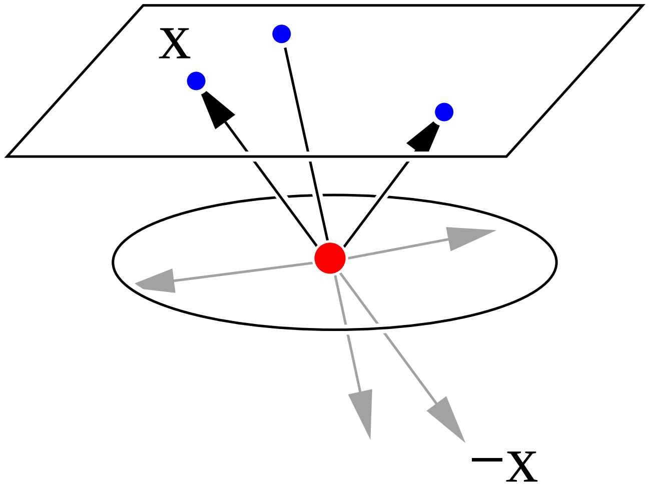


Perspective model

$\mathbf{x}$, $-\mathbf{x}$ represent
two different image points

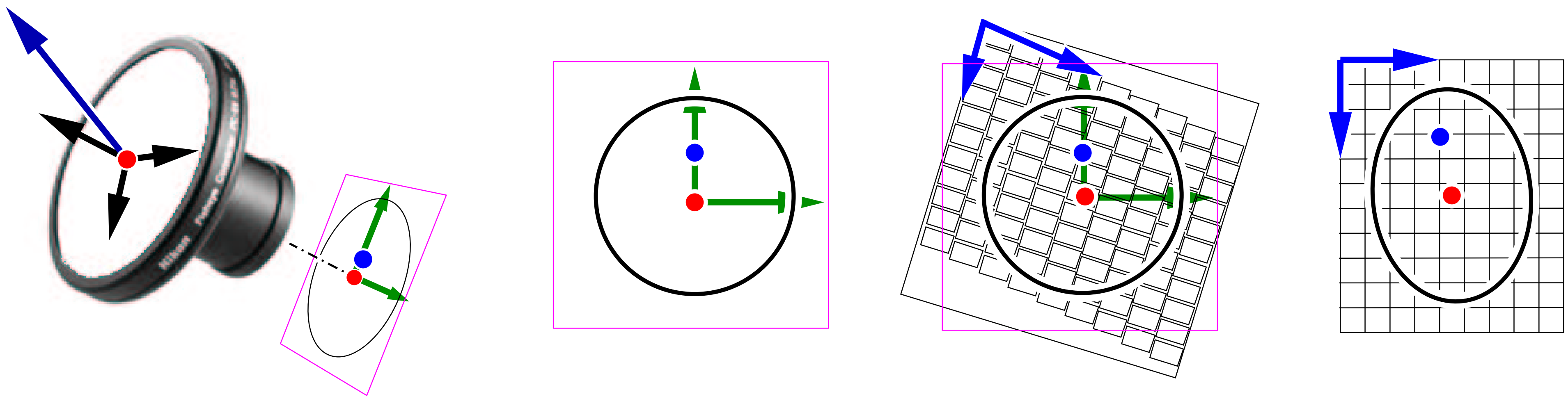
$\mathbf{x}$, $-\mathbf{x}$ represent
one image point

$$\exists \alpha > 0 : \ \alpha \mathbf{x} = \mathtt{P}\mathbf{X},$$

$\mathbf{X} \in \mathbb{R}^4$	...	scene point
$\mathtt{P} \in \mathbb{R}^{3\times 4}$	...	projection matrix
α	...	depth (always positive!)

Image Formation

Camera Sensor plane Digital image



. . . From the camera to the sensor plane →

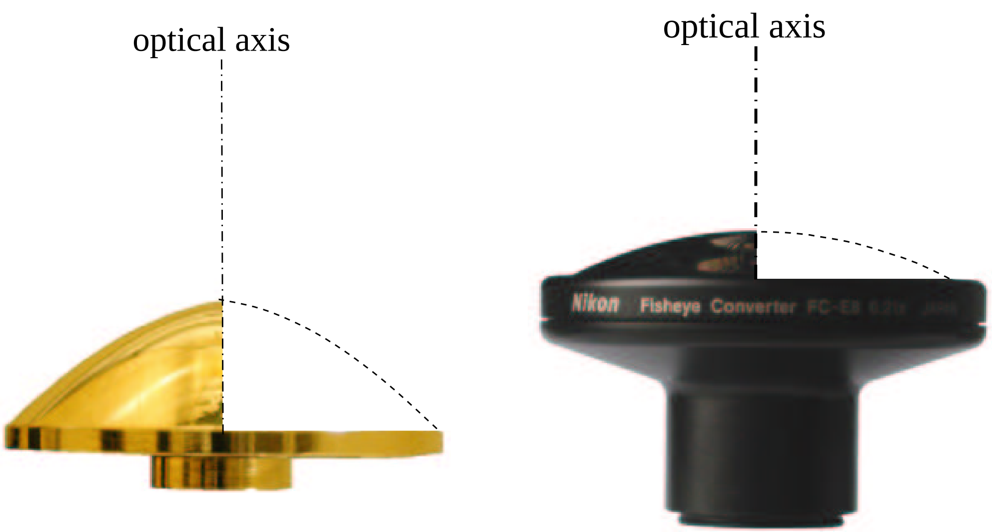
. . . From the sensor plane to the digital image →

Why two steps?

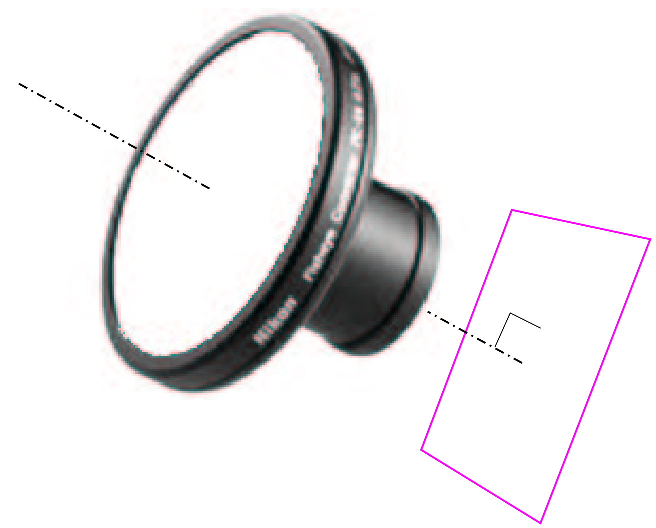
Scene coordinates — separated by non-linear projection from — image coordinates

Sensor plane ⊥ Optical axis

1) 2)

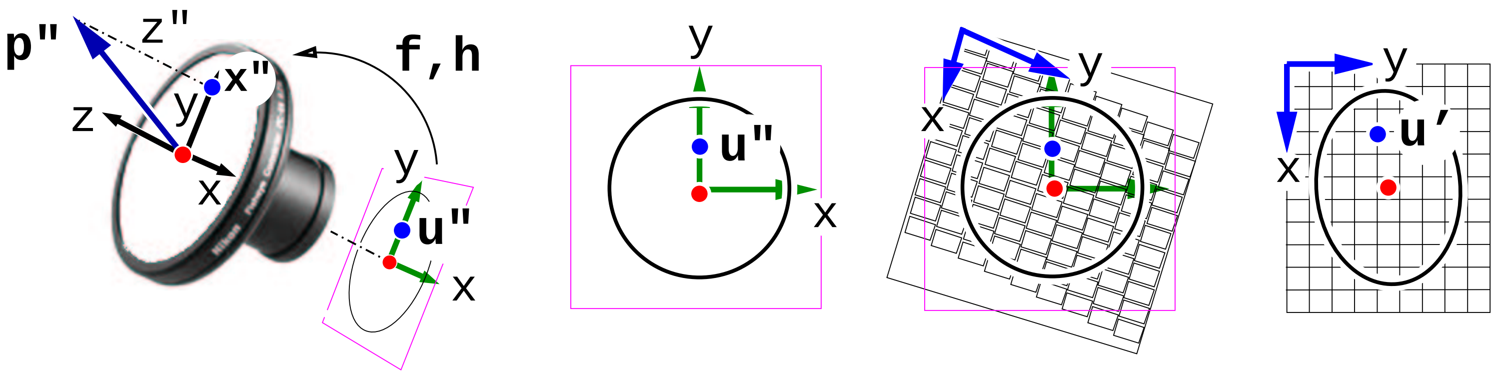


Mirrors & lenses are axially symmetric



Sensor plane ⊥ optical axis

Two steps of the calibration



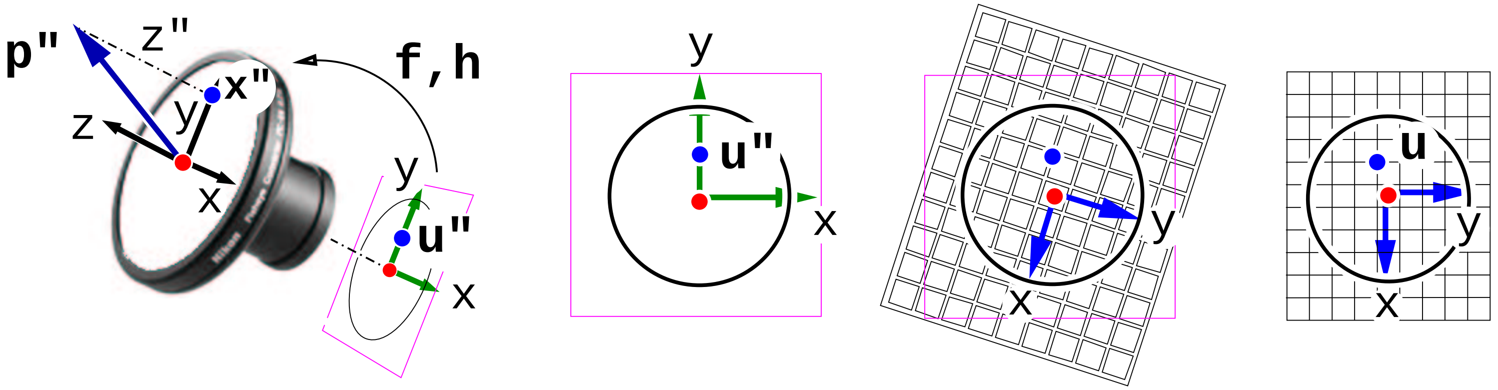
$$\cdots\ \mathbf{u}'' = \mathtt{A}'\mathbf{u}' + \mathbf{t}' \rightarrow$$

Step 1.

Image Coord. s. Calibration

$$\mathbf{u} = \mathtt{A}_C \mathbf{u}' + \mathbf{t}_C$$

$$\mathtt{A}_C = \frac{1}{\rho}\mathtt{R}^{-1}\mathtt{A}',\ \mathbf{t}_C = \mathbf{t}',\ \rho > 0$$



Metrically calibrated camera

$$\cdots\ \mathbf{u}'' = \rho\,\mathtt{R}\mathbf{u} \rightarrow$$

Step 2.

Calibration of non-linear f & h by Epipolar geometry estimation

Projection equation

$$\exists\, \alpha > 0: \quad \alpha \underbrace{\begin{pmatrix} f(\|\mathtt{A}'\mathbf{u}' + \mathbf{t}'\|)(\mathtt{A}'\mathbf{u}' + \mathbf{t}') \\ h(\|\mathtt{A}'\mathbf{u}' + \mathbf{t}'\|) \end{pmatrix}}_{\mathbf{p}} = \mathtt{P}\,\mathbf{X},$$

$\mathbf{X}$	...	scene point
$\mathbf{u}'$	...	image point
$\mathbf{p}$	...	vector in the spherical model
$\mathtt{P}$	...	projection matrix
$\mathtt{A}', \mathbf{t}'$	...	affine transformation
f, h	...	non-linear functions

Omnidirectional camera calibration

- B.Mičušík and T.Pajdla: Estimation of omnidirectional camera model from epipolar geometry. *CVPR*, 2003, Madison

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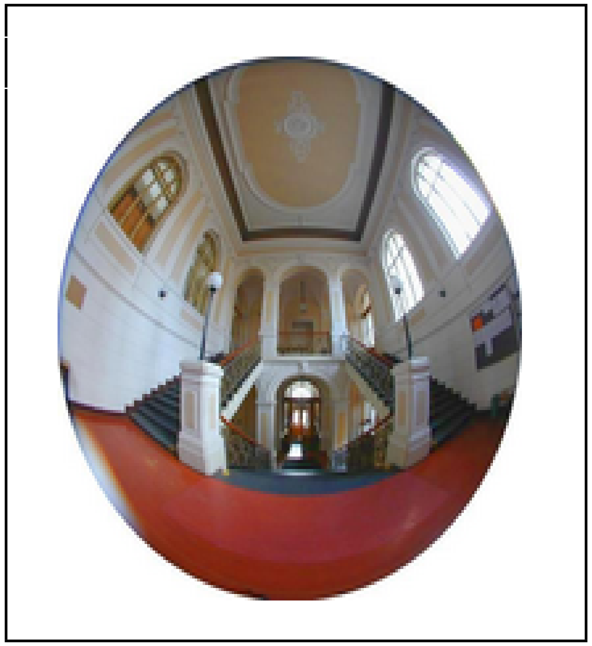

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After precalibration step

- an image of an optical axis, square pixels are obtained

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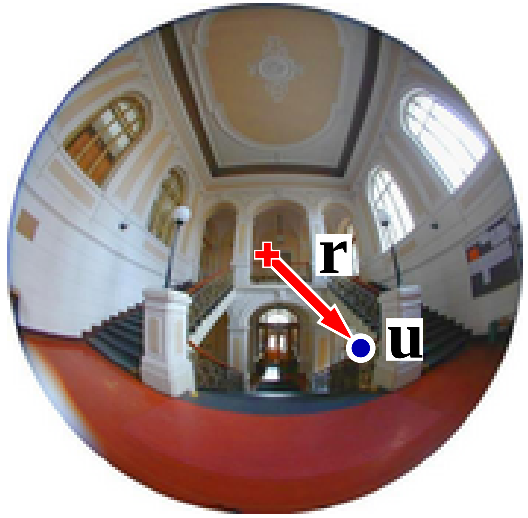
After precalibration step

- an image of an optical axis, square pixels are obtained
- a non-linear mapping becomes radially symmetric

From image point to 3D ray

From image point to 3D ray



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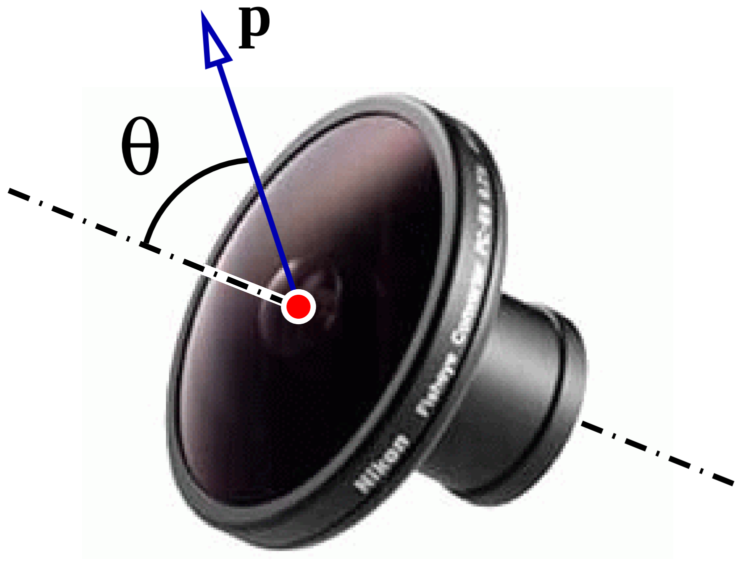

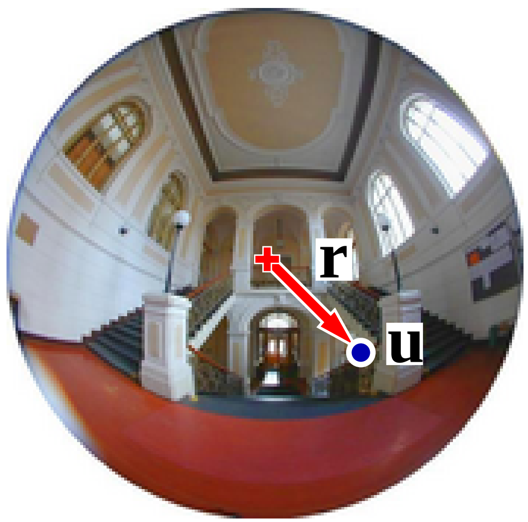

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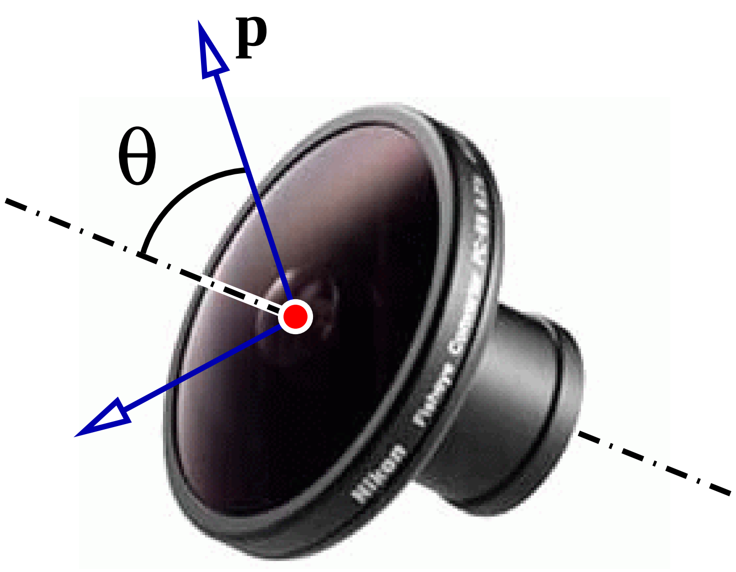

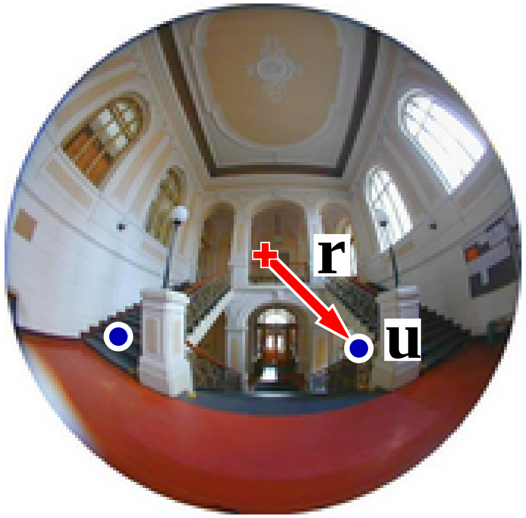

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- Relation between 3D vectors and image points is captured by a non-linear function, e.g.

$$\theta = \frac{ar}{1+br^2}$$

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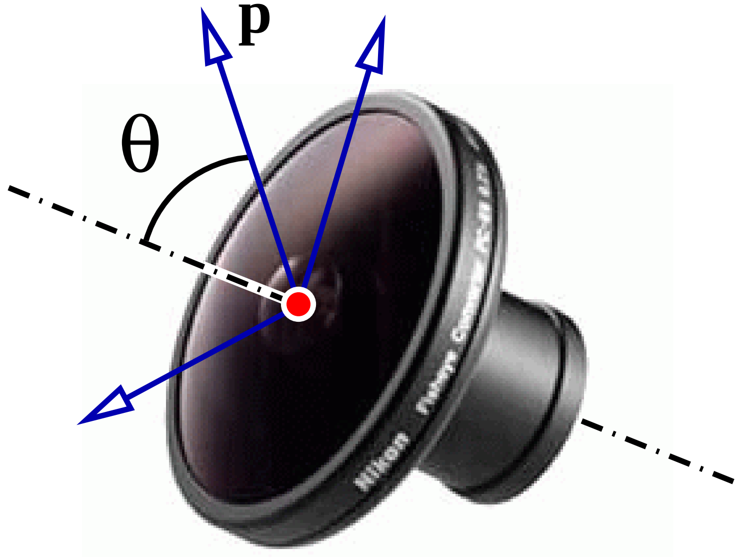

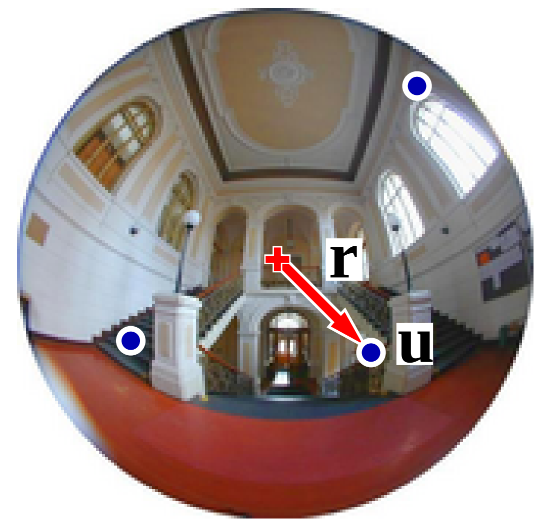

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$$\theta = \frac{ar}{1+br^2}$$

- 3D vector corresponding to an image point:

$$\mathbf{p} \simeq g(\mathbf{u}) = \begin{pmatrix} \mathbf{u} \\ w \end{pmatrix} = \begin{pmatrix} \mathbf{u} \\ f(\mathbf{u}, a, b) \end{pmatrix} = \begin{pmatrix} \mathbf{u} \\ \frac{r}{\tan\theta} \end{pmatrix} = \begin{pmatrix} \mathbf{u} \\ \frac{r}{\tan \frac{ar}{1+br^2}} \end{pmatrix}$$

details 1 2

Image point → 3D ray

- Nikon fish-eye lens:

$$\mathbf{p} \simeq \begin{pmatrix} \dfrac{\mathbf{u}}{\|\mathbf{u}\|} \\ \tan \frac{a\|\mathbf{u}\|}{1+b\,\|\mathbf{u}\|^2} \end{pmatrix},$$

- Sigma fish-eye lens:

$$\mathbf{p} \simeq \begin{pmatrix} \dfrac{\mathbf{u}}{\|\mathbf{u}\|} \\ \tan\left(\frac{1}{b}\arcsin\left(\frac{b\|\mathbf{u}\|}{a}\right)\right) \end{pmatrix},$$

- Para-catadioptric camera:

$$\mathbf{p} = \begin{pmatrix} \mathbf{u} \\ \frac{a^2-\|\mathbf{u}\|^2}{2a} \end{pmatrix},$$

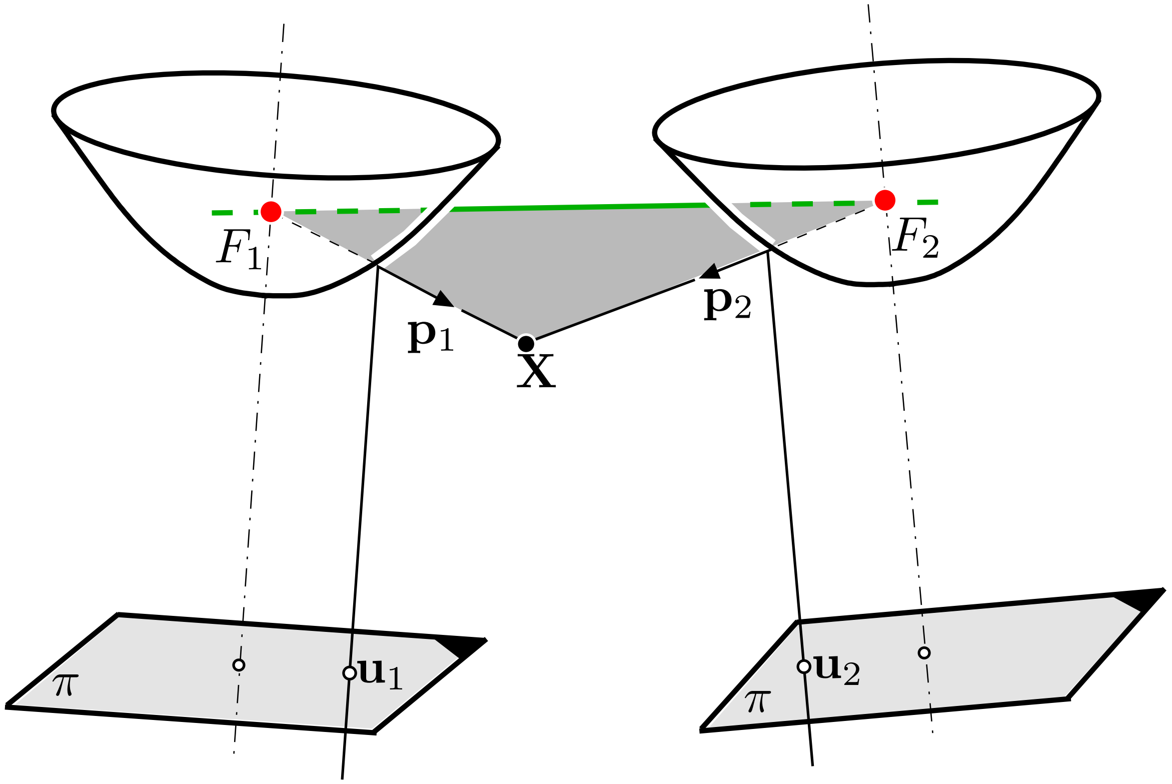
- Hyperbolic-catadioptric camera:

$$\mathbf{p} \simeq \frac{c^2\left(\sqrt{1+c^2}+\sqrt{\frac{\|\mathbf{u}''\|^2}{f^2}+1}\right)}{c^2-\frac{\|\mathbf{u}\|^2}{f^2}} \begin{pmatrix} -\frac{u}{f} \\ \frac{v}{f} \\ -1 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 2\sqrt{1+c^2} \end{pmatrix}.$$

- Approximated spherical-catadioptric camera:

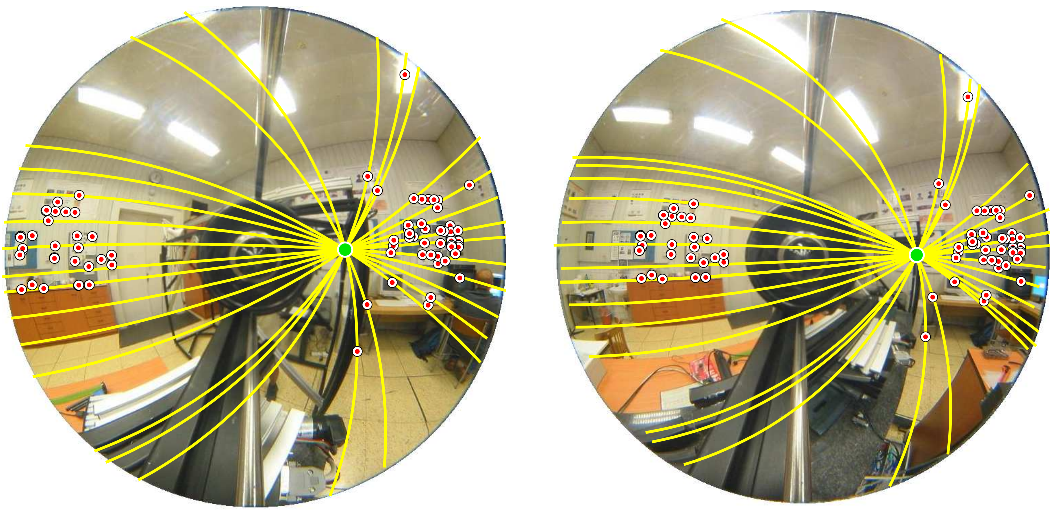
$$\mathbf{p} \simeq \frac{c+k-\sqrt{(c+k)^2-\left(\frac{\|\mathbf{u}\|^2}{f^2}+1\right)(c^2+2k\,c+k^2-1)}}{\frac{\|\mathbf{u}\|^2}{f^2}+1} \begin{pmatrix} -\frac{u}{f} \\ \frac{v}{f} \\ -1 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ c \end{pmatrix}$$

Epipolar Geometry - paracatadioptric camera

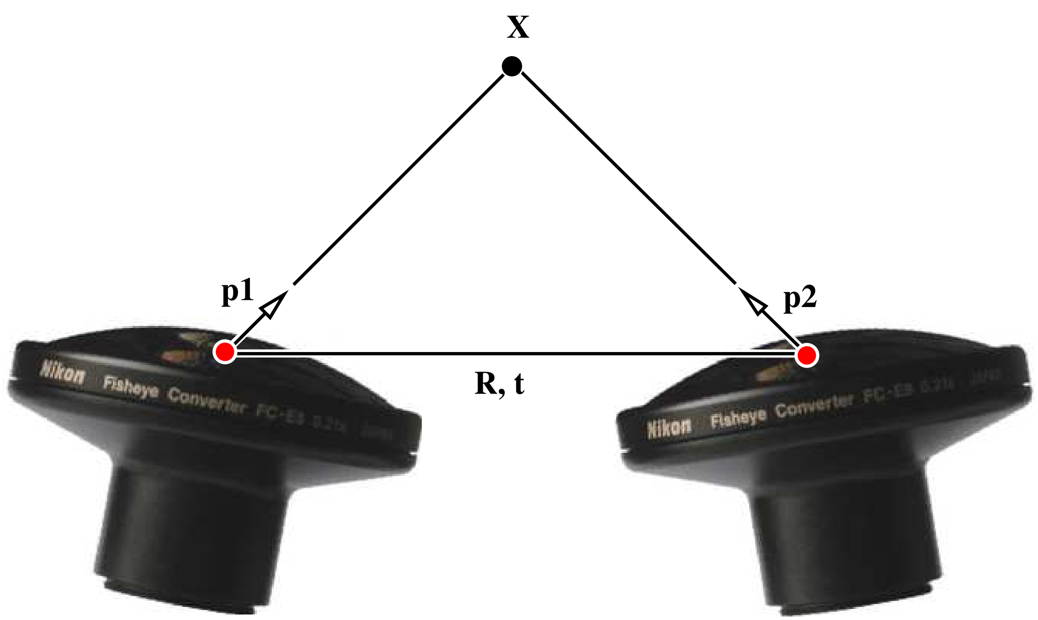


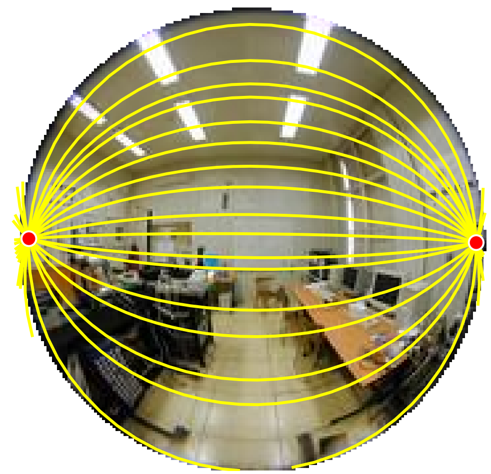
- central catadioptirc cameras possess EG (Svoboda et al ECCV 1998)

$$\mathbf{p}_2^\top \mathbf{F}\, \mathbf{p}_1 = 0$$



Epipolar geometry





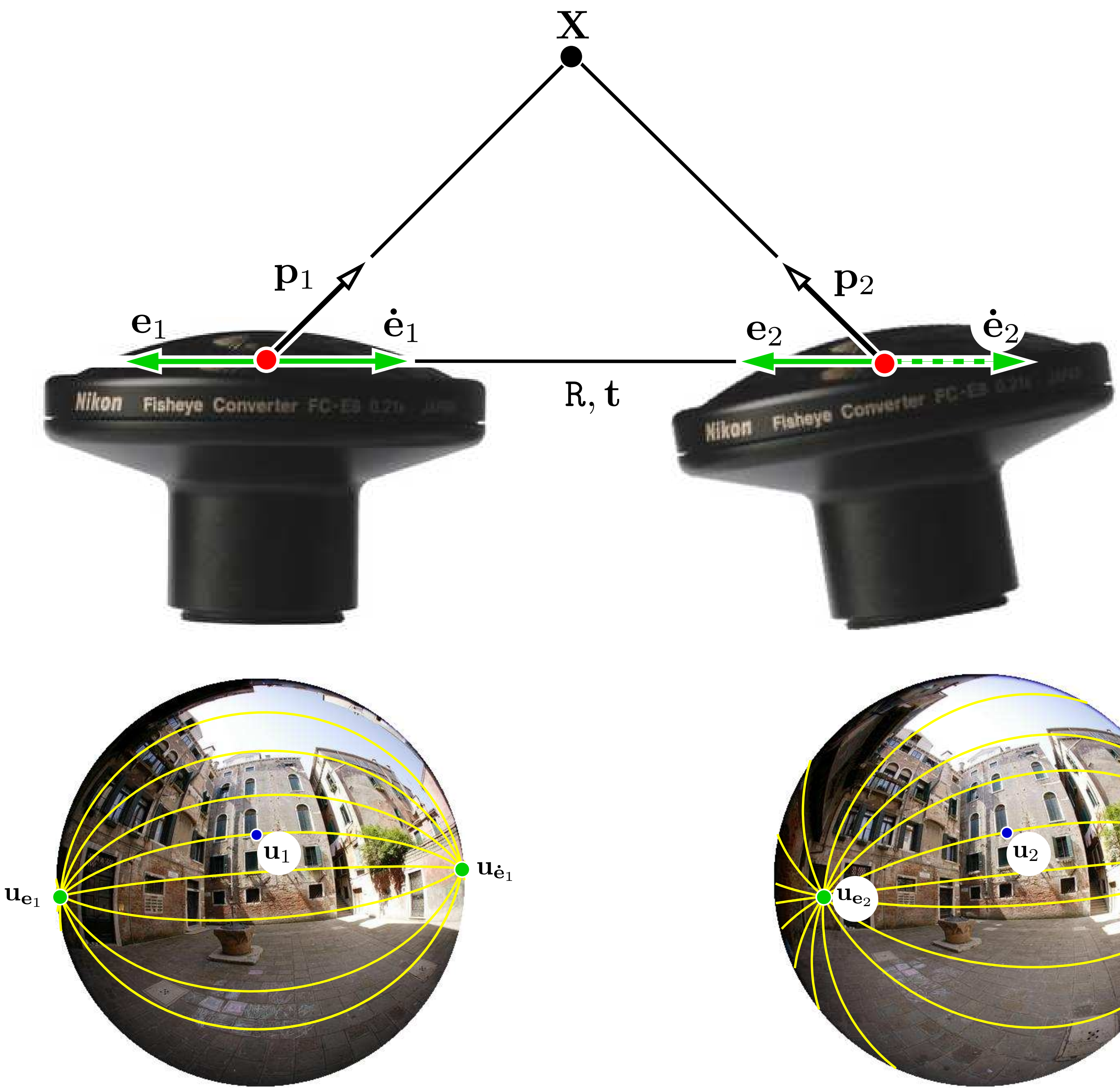
Epipolar constraint holds for every central camera

$$\mathbf{p}_2^\top \mathbf{F}\, \mathbf{p}_1 = 0$$

Epipolar curves are . . .

1. conics for central catadioptric cameras (Svoboda & Pajdla IJCV 2002)
2. non-conics for wide-angle dioptric cameras (Micusik & Pajdla CVPR 2003)

Why two epipoles?



Theory of omnidirectional camera calibration

- Taylor series of g with respect to parameters a, b

$$\mathbf{p} \quad \simeq \quad g(\mathbf{u}) = \begin{pmatrix} \mathbf{u} \\ \frac{r}{\tan \frac{ar}{1+br^2}} \end{pmatrix} \approx \mathbf{x} + a\mathbf{s} + b\mathbf{t}$$

Theory of omnidirectional camera calibration

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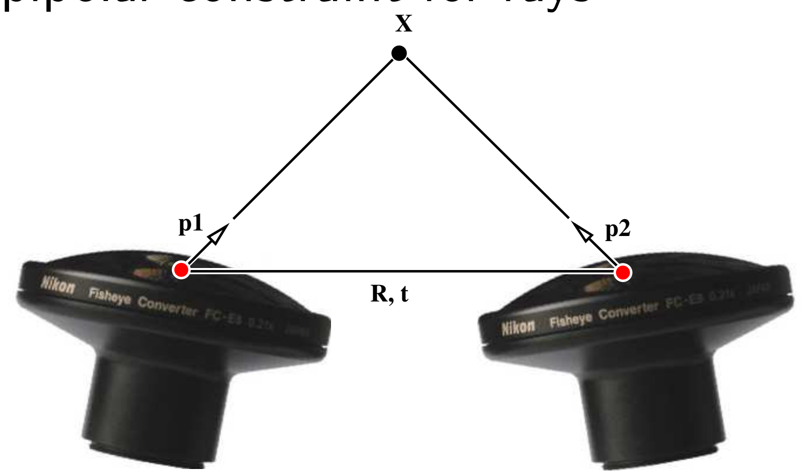
$$\mathbf{p} \quad \simeq \quad g(\mathbf{u}) = \left(\begin{array}{c} \mathbf{u} \\ \frac{r}{\tan \frac{ar}{1+br^2}} \end{array} \right) \approx \mathbf{x} + a\mathbf{s} + b\mathbf{t}$$

- Epipolar constraint for rays



$$\mathbf{p}_2^\top \mathtt{F}\, \mathbf{p}_1 = 0$$

$$(\mathbf{x}_2 + a\mathbf{s}_2 + b\mathbf{t}_2)^\top \mathtt{F} (\mathbf{x}_1 + a\mathbf{s}_1 + b\mathbf{t}_1) = 0$$

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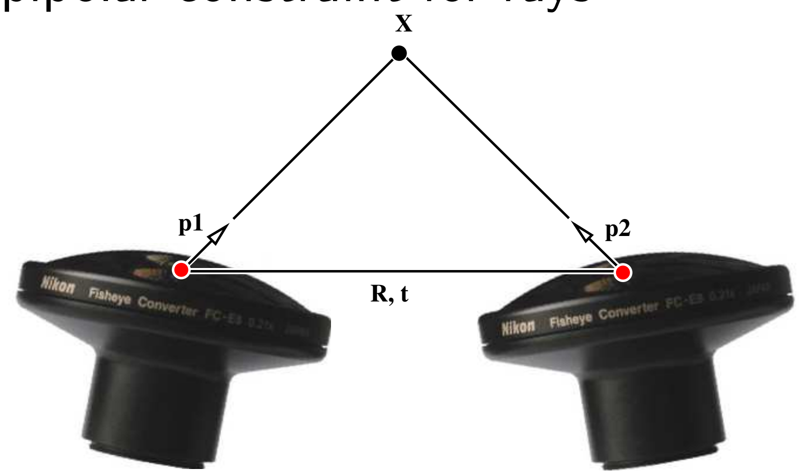

$$\mathbf{p}_2^\top \mathtt{F}\, \mathbf{p}_1 = 0$$

$$(\mathbf{x}_2 + a\mathbf{s}_2 + b\mathbf{t}_2)^\top \mathtt{F} (\mathbf{x}_1 + a\mathbf{s}_1 + b\mathbf{t}_1) = 0$$

- leads to the Quadratic Eigenvalue Problem (QEP)

$$(\mathtt{D}_1 + a\mathtt{D}_2 + a^2\mathtt{D}_3)\mathbf{h} = 0 \,,$$

where $\mathtt{D}_\mathtt{i}$ are known and $\mathbf{h} = [\, f_1 \;\; f_2 \;\; f_3 \;\; f_4 \;\; f_5 \;\; f_6 \;\; f_7 \;\; f_8 \;\; f_9 \;\; bf_3 \;\; bf_6 \;\; bf_7 \;\; bf_8 \;\; bf_9 \;\; b^2 f_9 \,]^\top$.

- QEP can be solved by MATLAB using `polyeig`

Results of omnidirectional camera calibration

- the calibrated camera, i.e. the parameters of a nonlinear camera model, $\mathtt{A}'$ and $\mathbf{t}'$

$$\theta = \frac{ar}{1+br^2} \,,$$

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- the essential matrix

$$\mathtt{E} = [\mathbf{t}]_\times \mathtt{R} \,,$$

Results of omnidirectional camera calibration

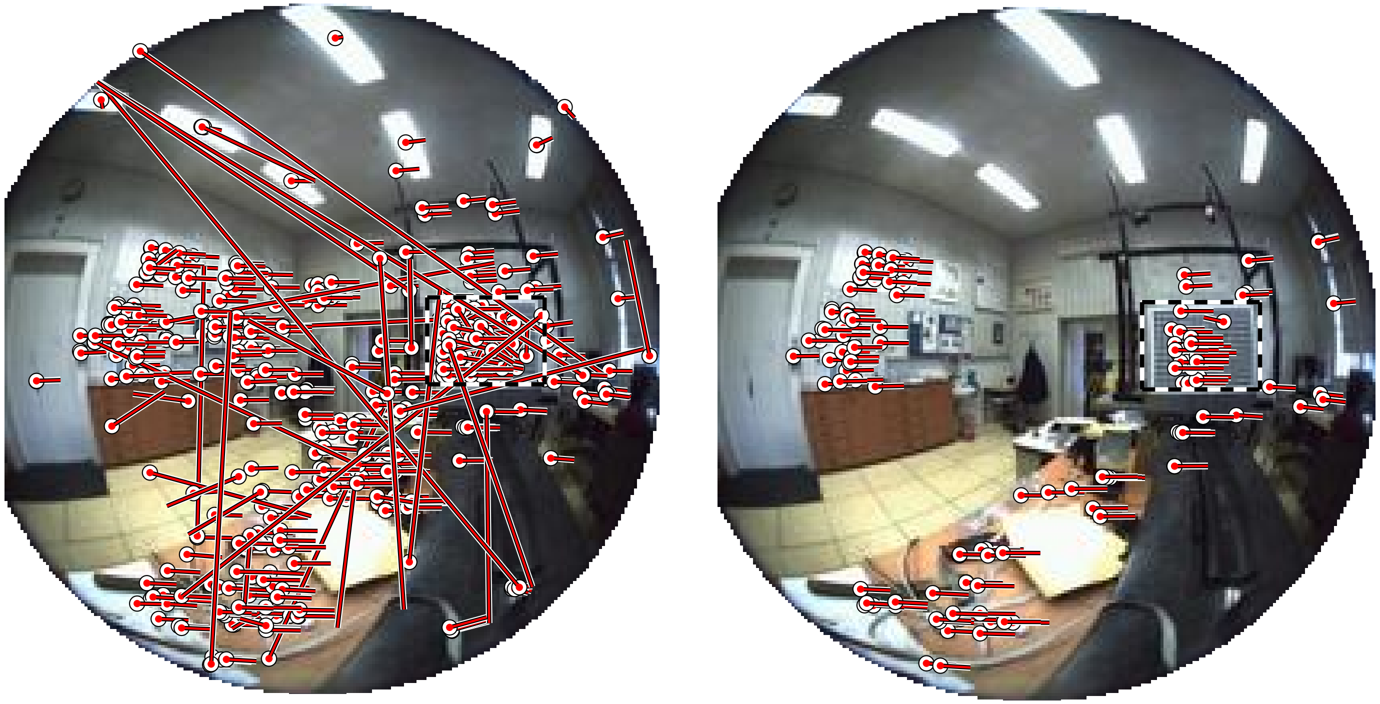
- the calibrated camera, i.e. the parameters of a nonlinear camera model, $\mathtt{A}'$ and $\mathbf{t}'$

$$\theta = \frac{ar}{1+br^2} ,$$

- the essential matrix

$$\mathtt{E} = [\mathbf{t}]_\times \mathtt{R} ,$$

- correct point correspondences (inliers)

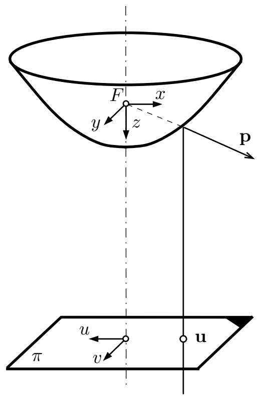


more 1

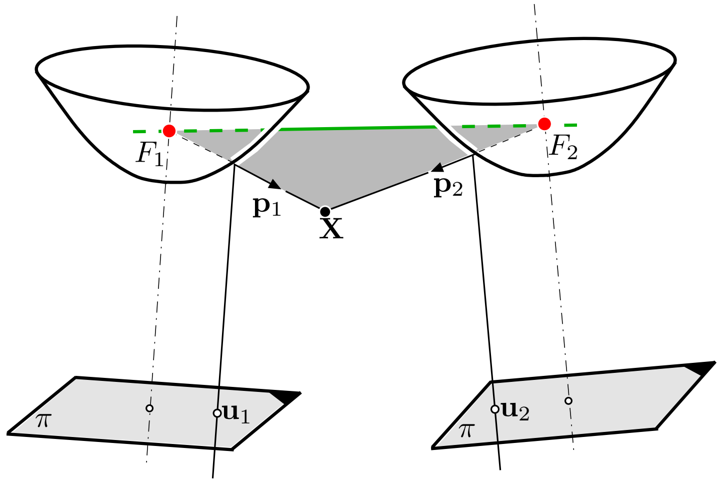
Remark - PCD camera calibration does not need linearization

- 3D vector

$$\mathbf{p} = \left(-u, \quad v, \quad \frac{a^2 - r^2}{2a} \right)^\top$$



- Epipolar constraint for rays



$$\mathbf{p}_2^\top \mathbf{F} \mathbf{p}_1 = 0$$

$$\left(-u_2, \quad v_2, \quad \frac{a^2 - r_2^2}{2a} \right) \mathbf{F} \left(-u_1 \quad v_1, \quad \frac{a^2 - r_1^2}{2a} \right)^\top = 0$$

- leads to the Polynomial Eigenvalue Problem (PEP)

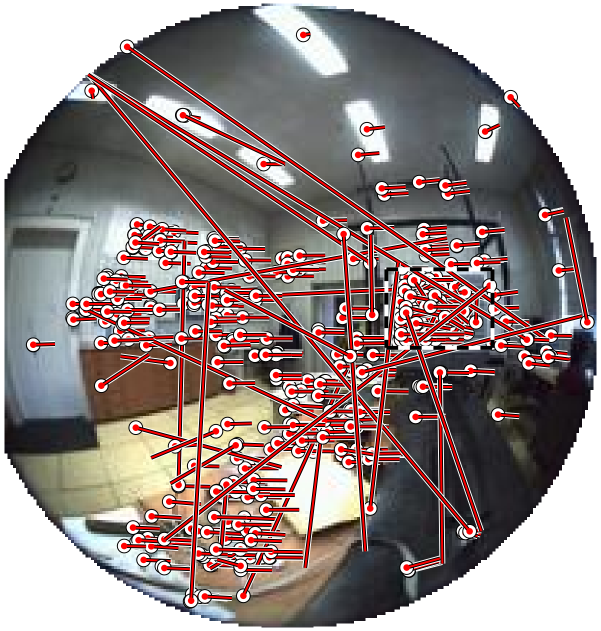
$$(\mathtt{D}_1 + a\mathtt{D}_2 + \ldots + a^4\mathtt{D}_5)\mathbf{f} = \mathbf{0} \; ,$$

where $\mathtt{D_i} \in \mathbb{R}^{9\times 9}$ are known and $\mathbf{f} = [\, \mathtt{F}_{11} \;\; \mathtt{F}_{12} \;\; \mathtt{F}_{13} \;\; \mathtt{F}_{21} \;\; \ldots \;\; \mathtt{F}_{33} \,]^\top$.

- PEP can be solved by MATLAB using `polyeig`

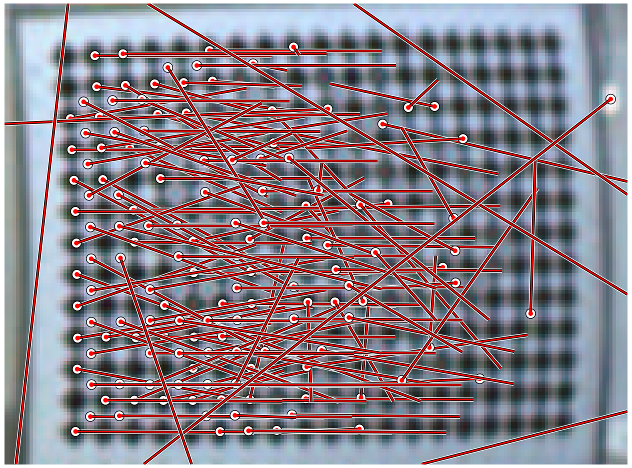
APPLICATIONS

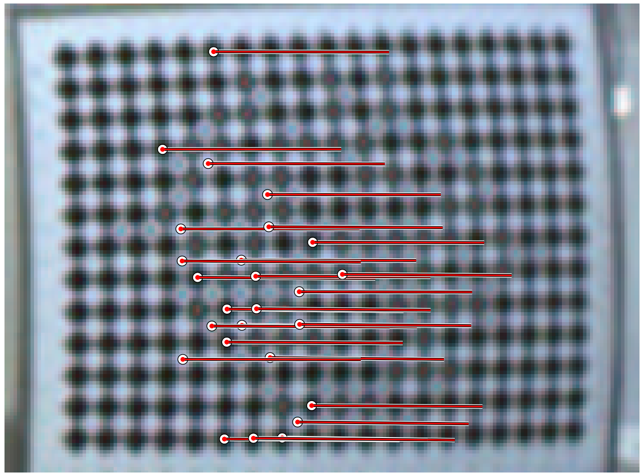
Correspondences - example



Tentative correspondences using similarity (Matas et al BMVC 2002)

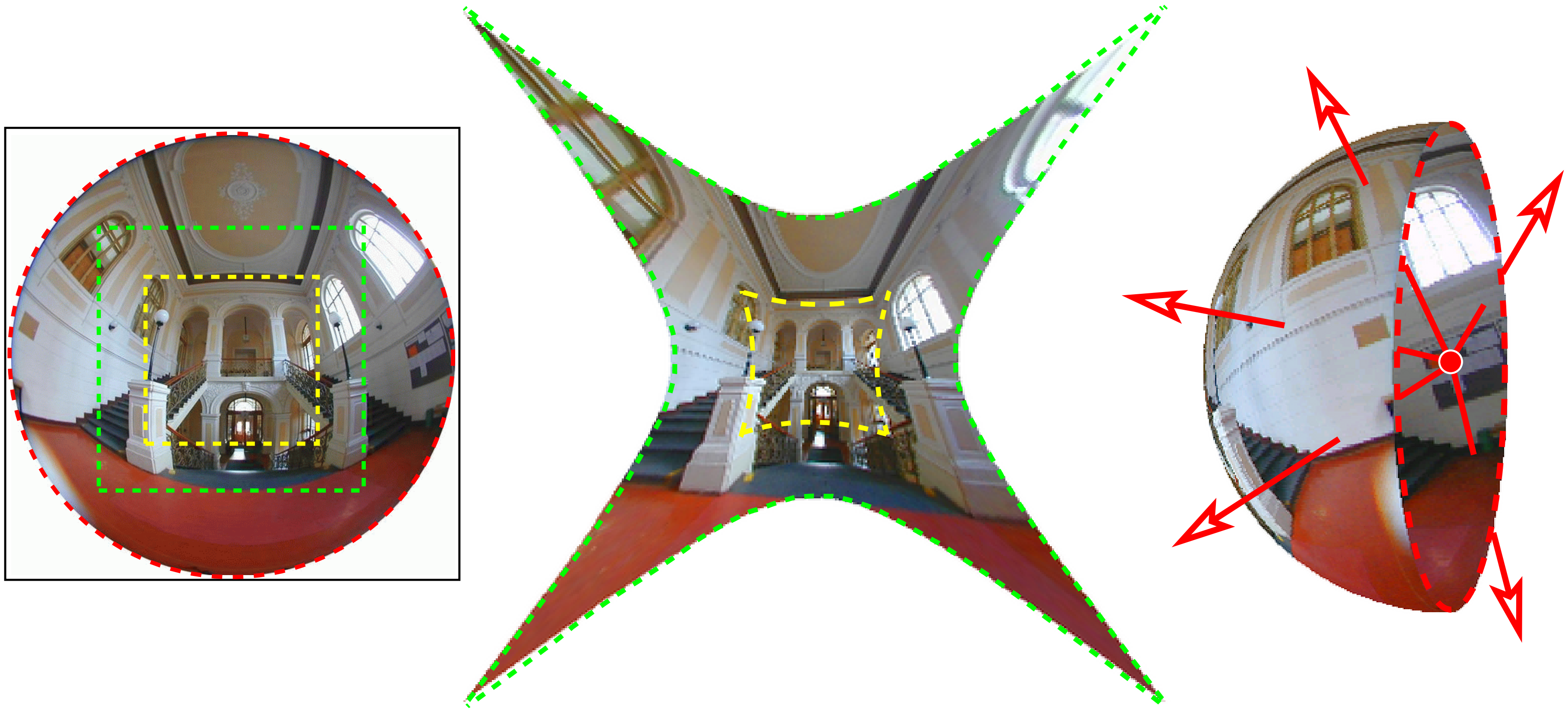
Inliers satisfying epipolar geometry of Nikon FC-E8 (Micusik & Pajdla SCIA 2003)





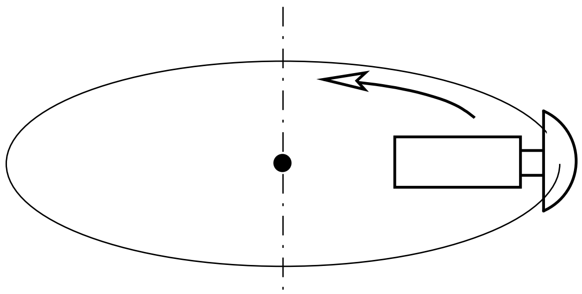
'Perspectivisation' of images

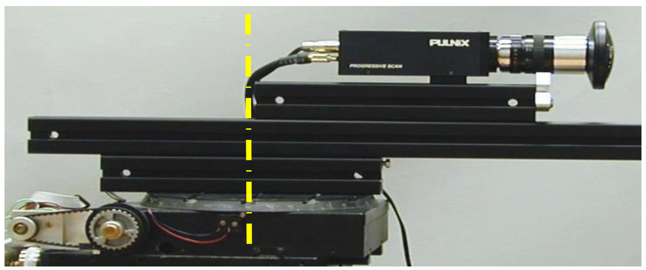
- Calibration available

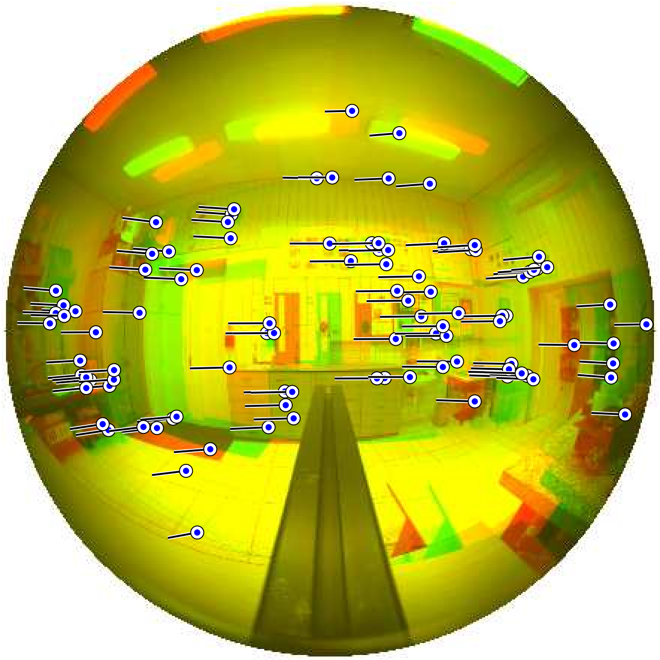


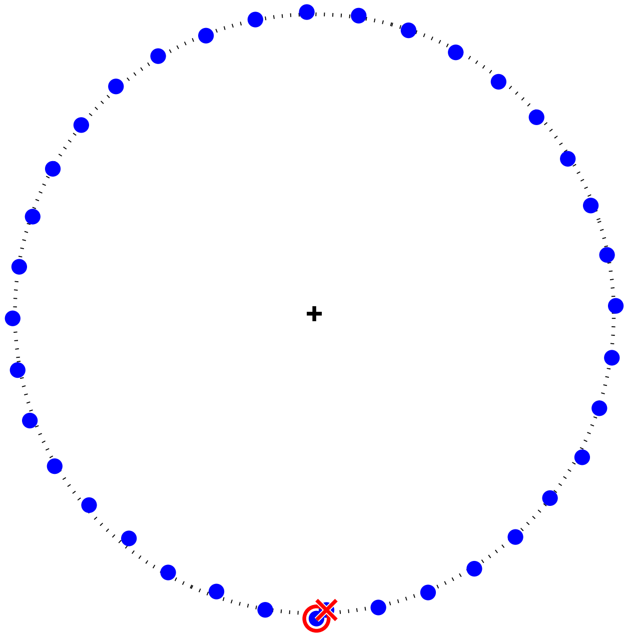
- a perspective image can be generated only for a limited (e.g. $< 160^\circ$) field of view
- the whole image can be represented on a sphere

Trajectory estimation







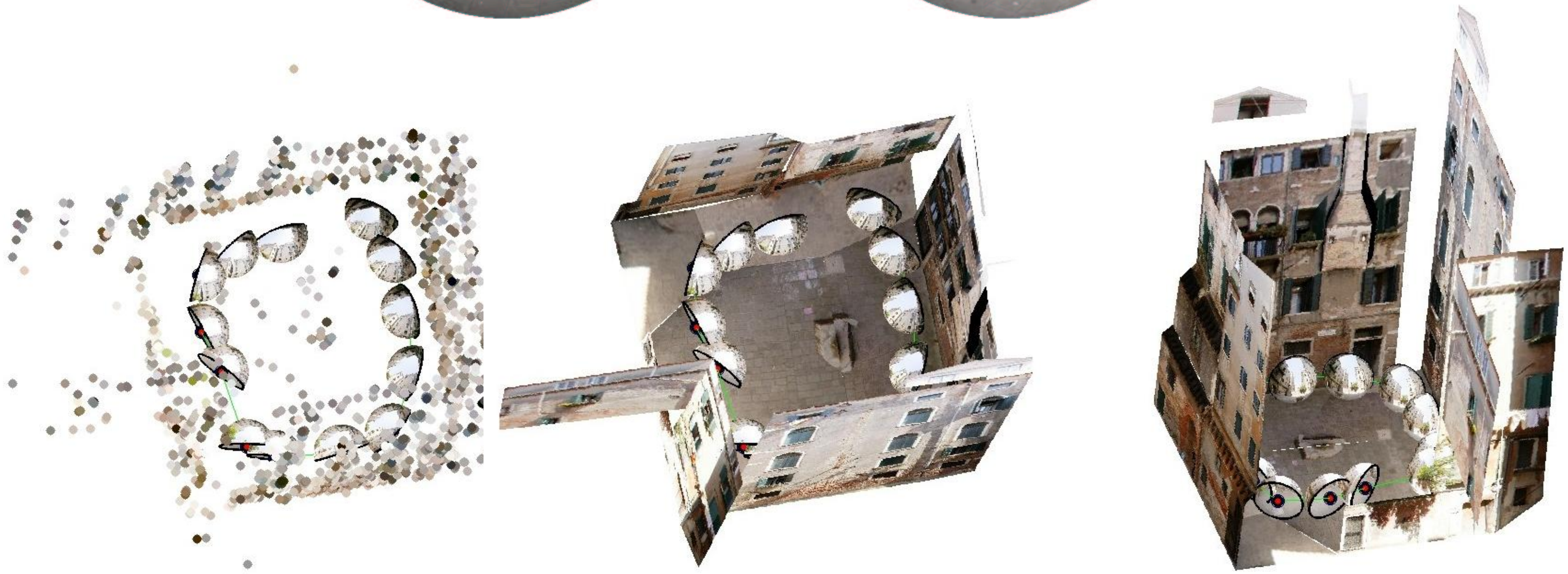


- Nikon FC–E8 lens mounted on a digital camera with resolution 1017×1008 pxls was rotated along a circle, correspondences obtained by *boujou*, 2d3 Ltd.
- relative camera rotations and directions of translations are computed from essential matrices

3D Metric Reconstruction - I

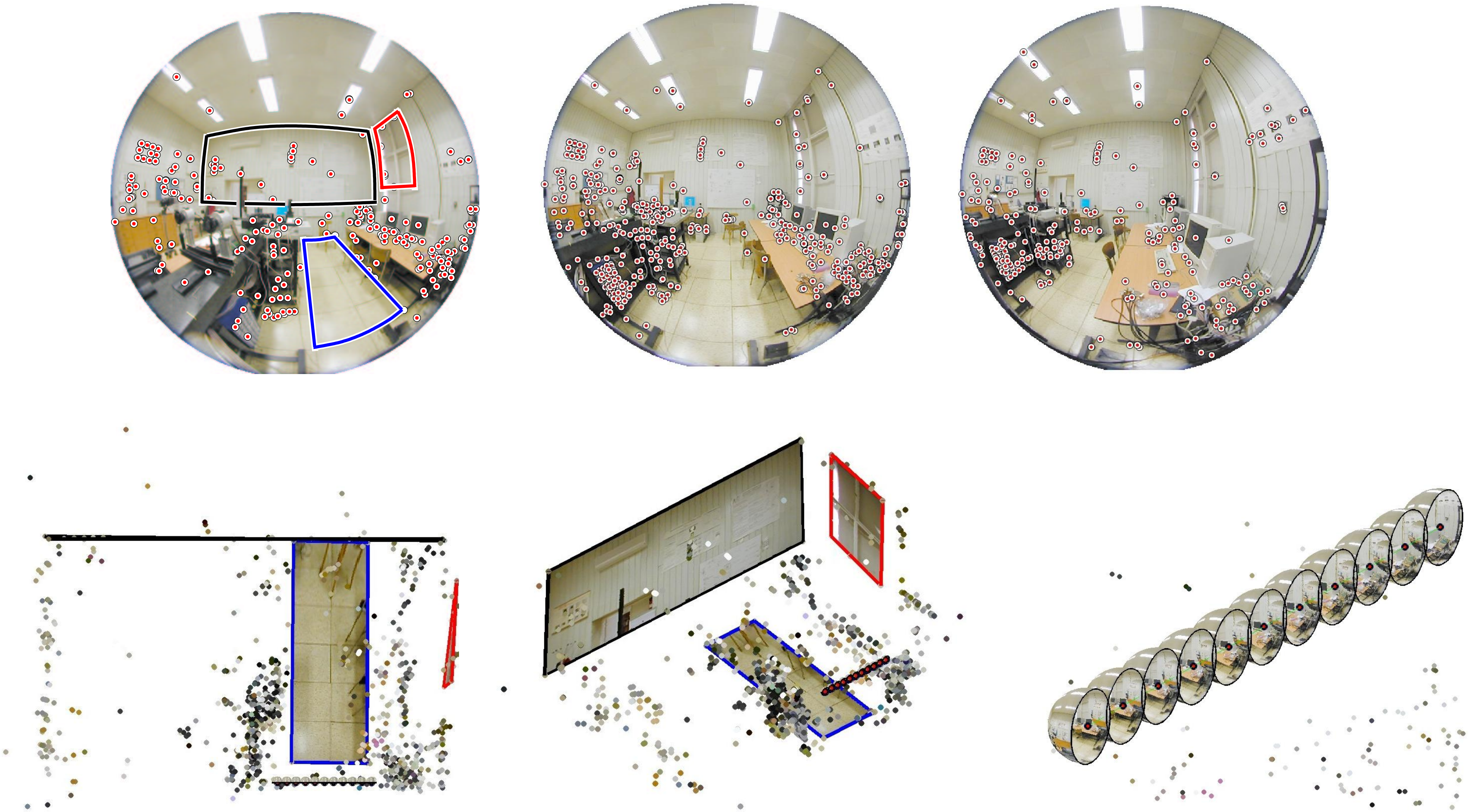
Images → Calibration form EG's (Micusik & Pajdla CVPR 2003), → 3D metric reconstruction from two images(Micusik & Martinec & Pajdla ACCV 2004).

3D Metric Reconstruction - II



Images → Calibration form EG's → Projective Factorization (Martinec & Pajdla ECCV 2002), see details in Micusik & Martinec & Pajdla ACCV 2004.

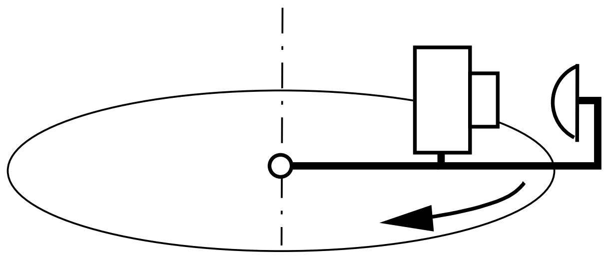
3D Metric Reconstruction - III

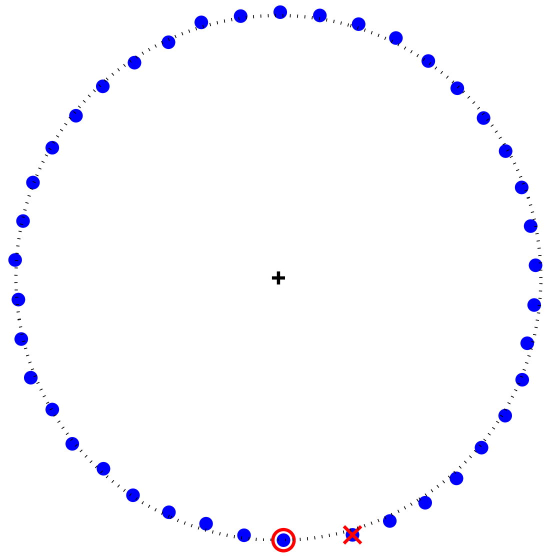


Images → Calibration form EG's → Projective Factorization (Martinec & Pajdla ECCV 2002), see details in Micusik & Martinec & Pajdla ACCV 2004.

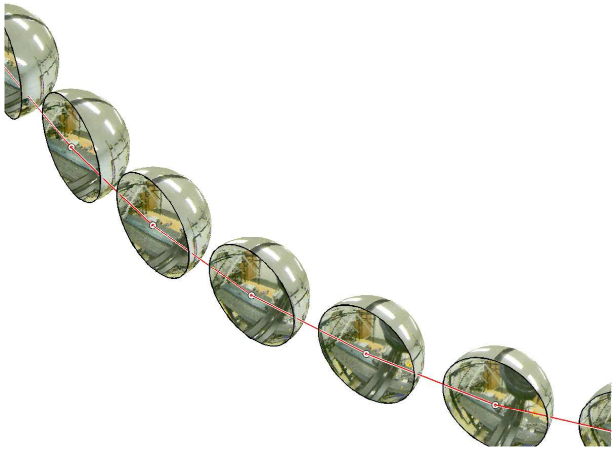
Trajectory estimation of PCD camera

- PCD camera mounted on a turntable and rotated along a circle





- correctly recovered positions and orientations of cameras



Part 2.

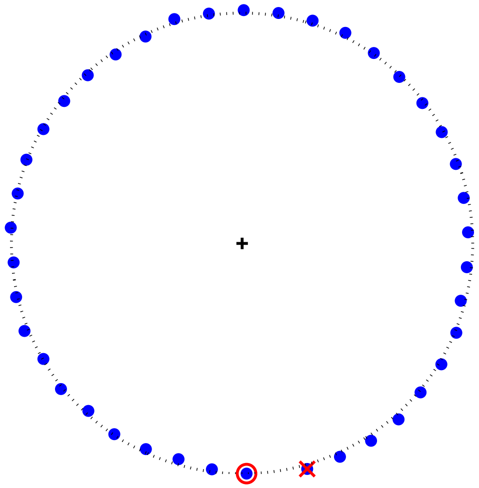
Real non-central catadioptric cameras

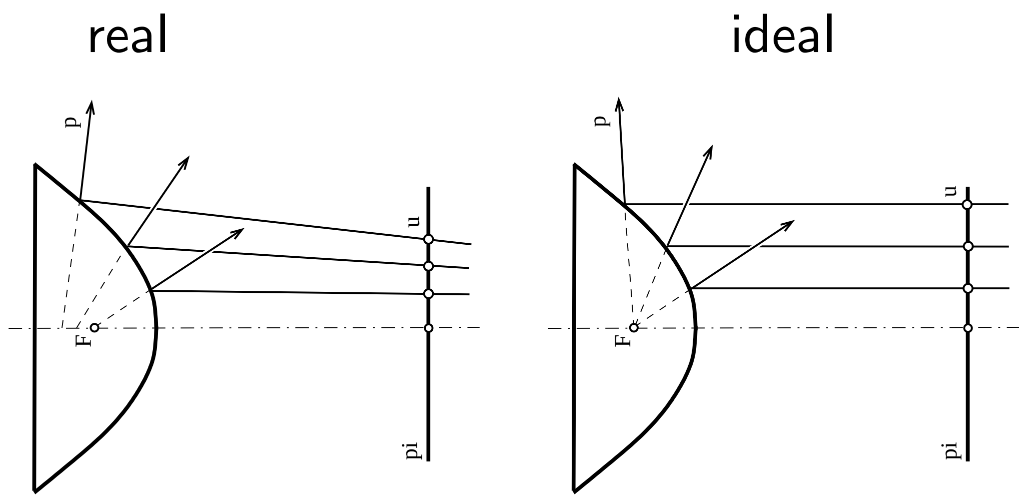
models

&

stereo geometries

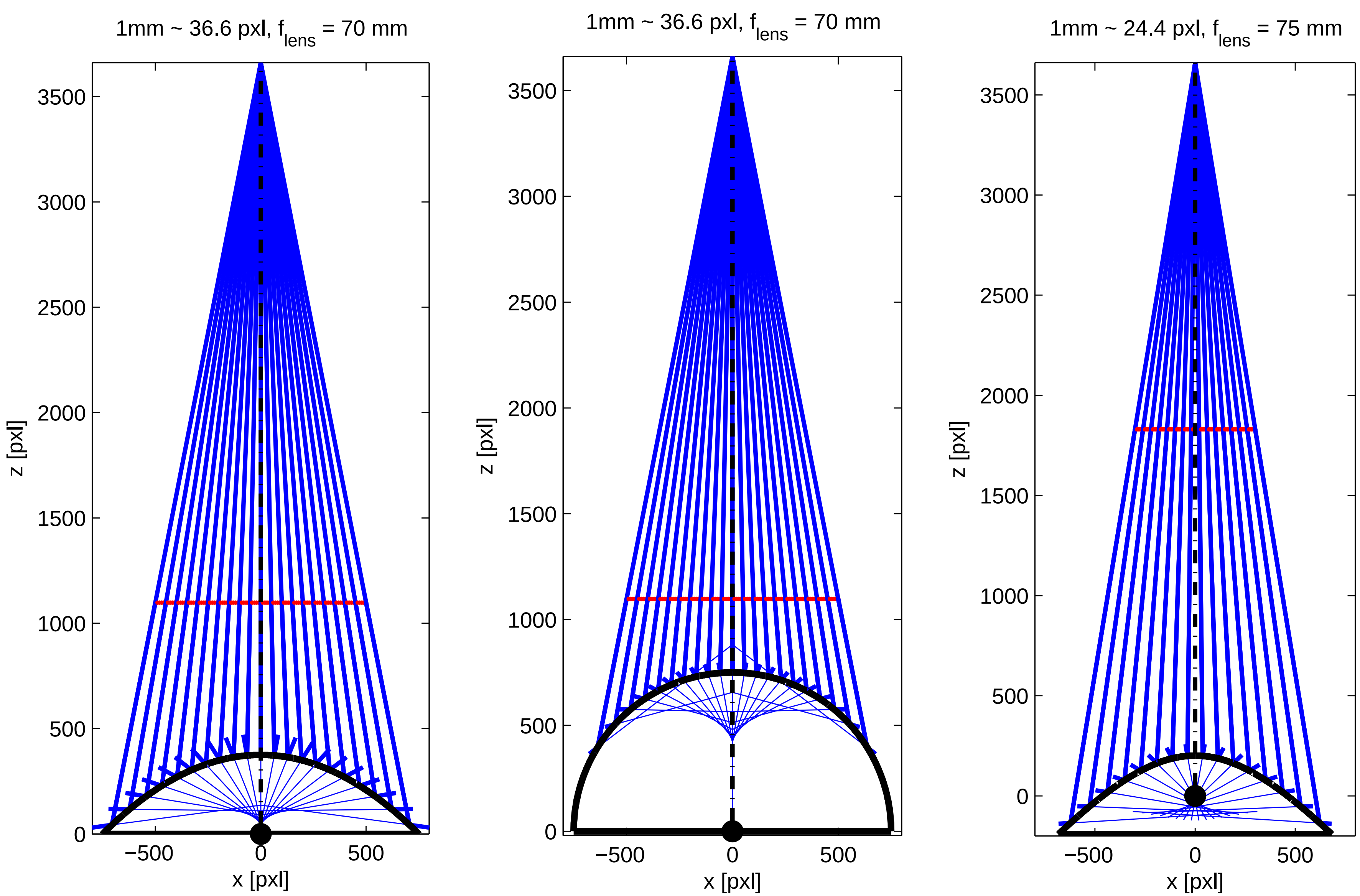
Real non-central catadioptric cameras





Non-central projection $\rightarrow$ Trajectory start $\neq$ Trajectory end

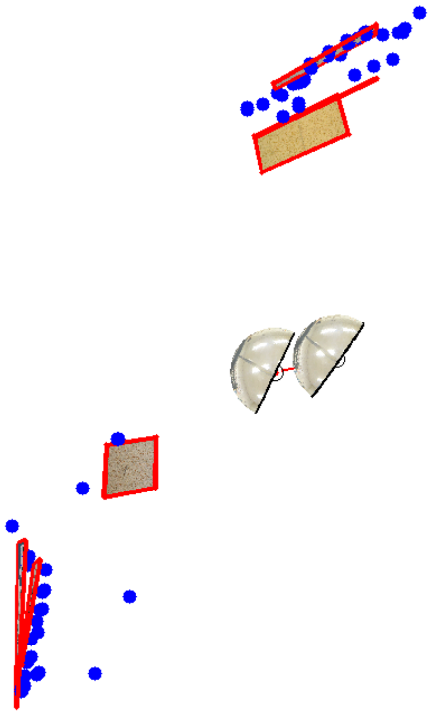
Rays are tangent to a caustic

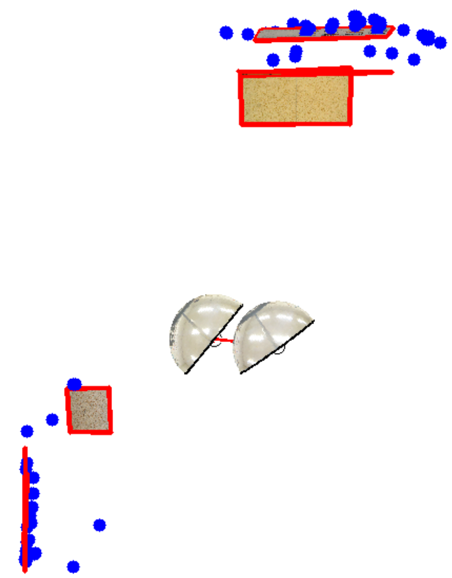


Parabolic Spherical Hyperbolic mirror

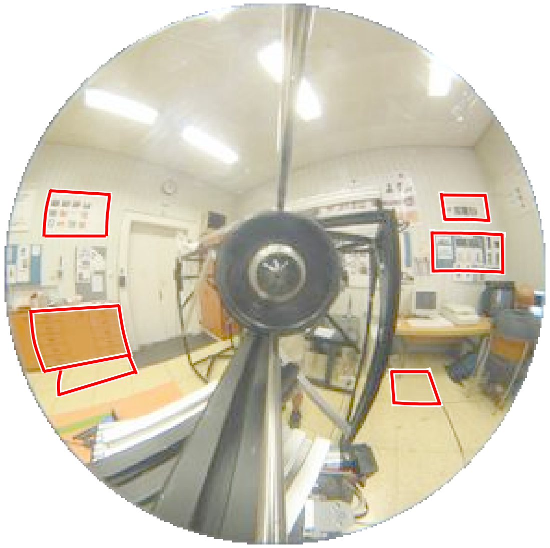
Rays reflected by the mirror are tangent to a caustic surface.

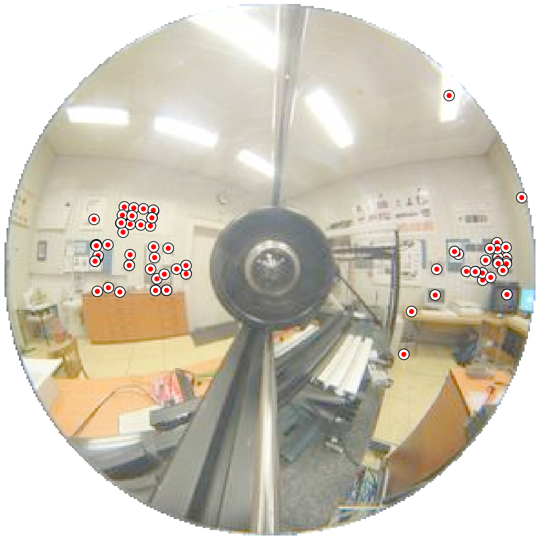
Non-central vs. Central model





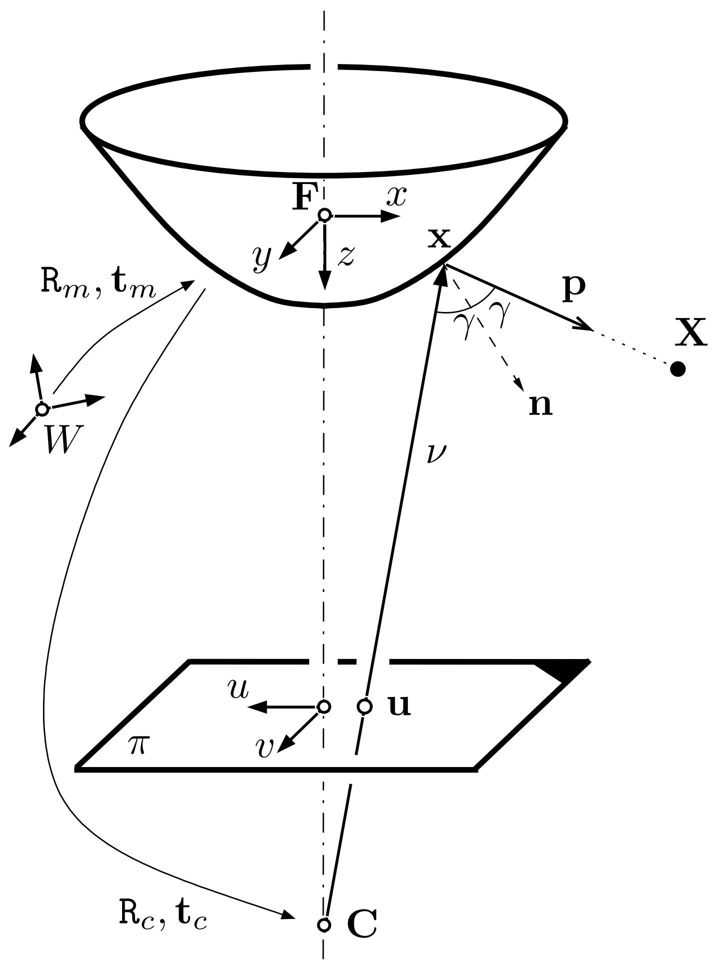
Central model (angles are wrong)   Non-central model (angles are correct)





Precise non-central camera model

- B. Mičušík and T.Pajdla: Autocalibration & 3D reconstruction with non-central omnidirectional cameras. *CVPR*, 2004, USA
- A non-central model from image points to 3D rays can be derived by using the perspective projection and law of reflection.



for every $\mathbf{u}$ there is $(\mathbf{x}_w; \mathbf{p}_w)$

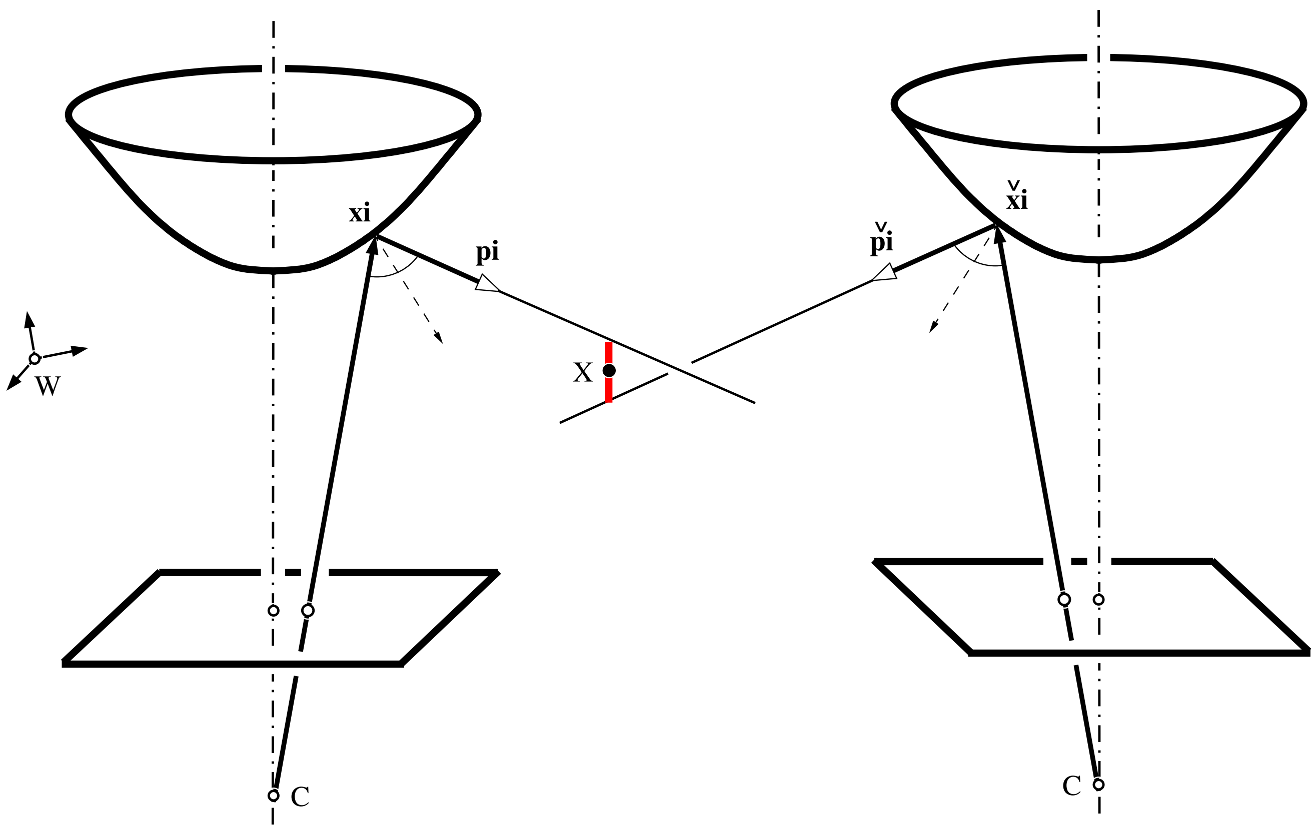
$$\mathbf{x}_w = f(\mathbf{u}, \mathbf{a}, \mathtt{R}_m, \mathbf{t}_m, \mathtt{R}_c, \mathbf{t}_c, \mathtt{K})$$

$$\mathbf{p}_w = f(\mathbf{u}, \mathbf{a}, \mathtt{R}_m, \mathbf{t}_m, \mathtt{R}_c, \mathbf{t}_c, \mathtt{K})$$

3D metric reconstruction

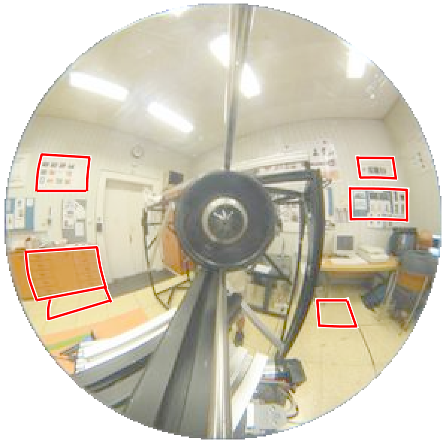
- 3D metric reconstruction is obtained by

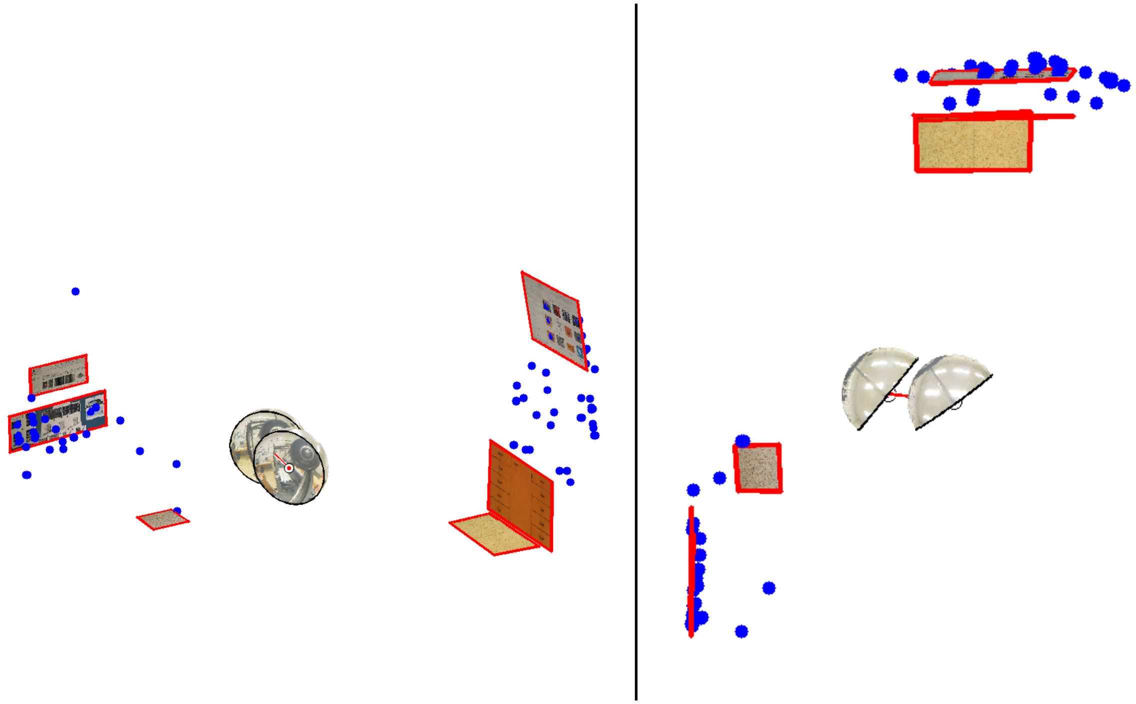
$$\mathcal{R}_M = \underset{\mathbf{a},\mathtt{R}_c,\mathbf{t}_c,\mathtt{R}_m,\mathbf{t}_m,\mathtt{K}}{\operatorname{argmin}} \sum_{i=1}^{N} \left(\frac{\left| \left(\mathbf{x}_w^i - \check{\mathbf{x}}_w^i\right) \cdot \left(\mathbf{p}_w^i \times \check{\mathbf{p}}_w^i\right) \right|}{\left|\mathbf{p}_w^i \times \check{\mathbf{p}}_w^i\right|} \right)^2$$

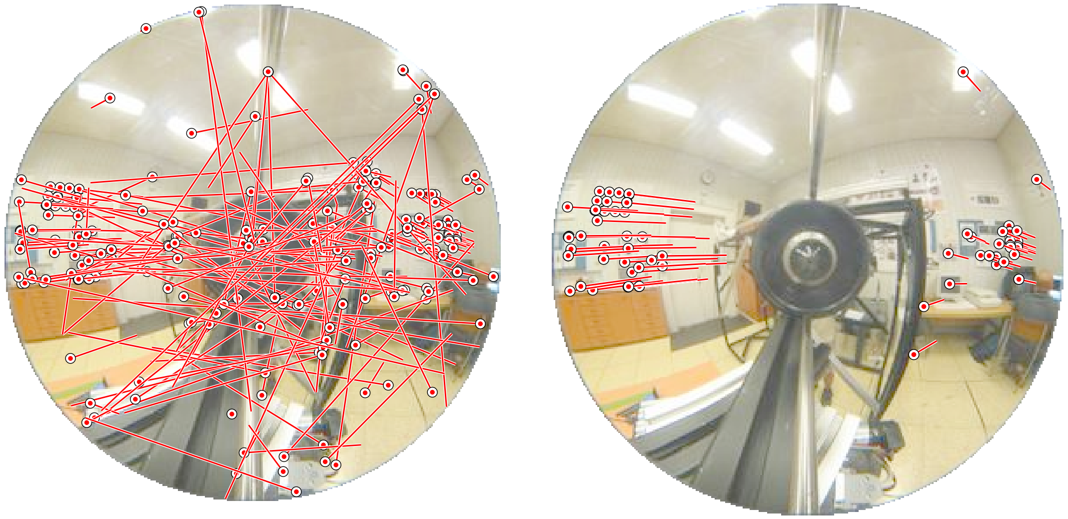


- Since the camera is calibrated, it is equivalent to minimizing the image reprojection errors

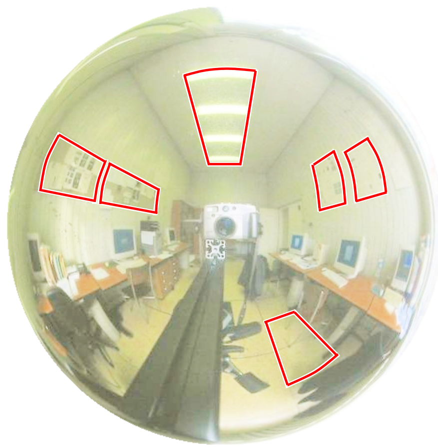
3D reconstruction - parabolic mirror

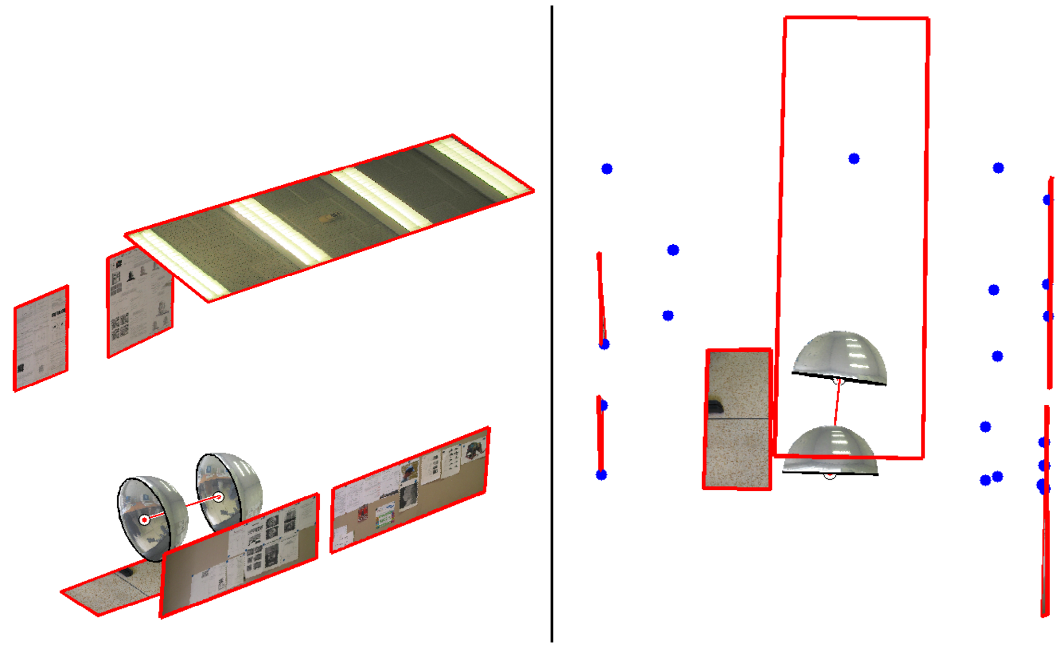


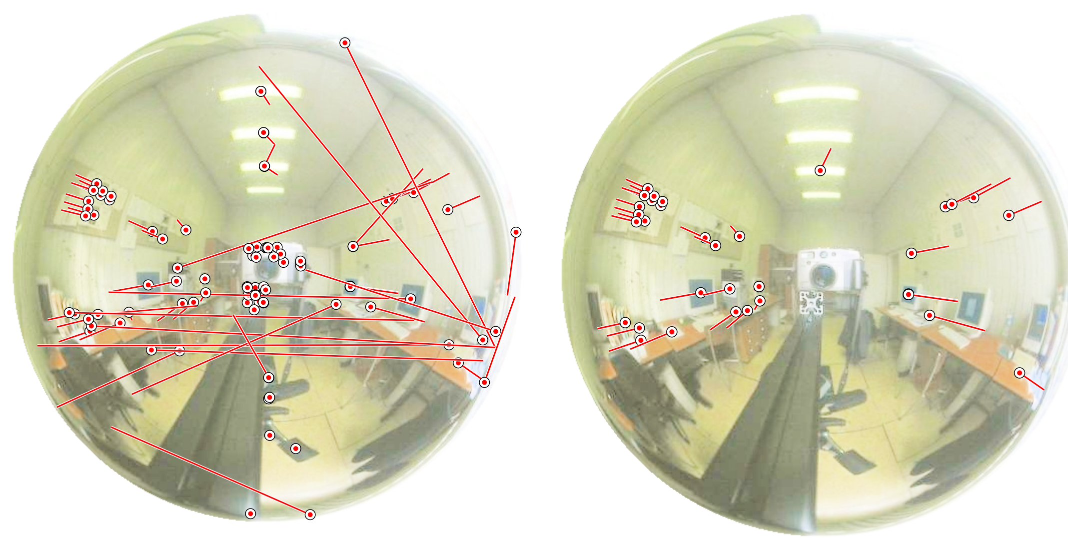




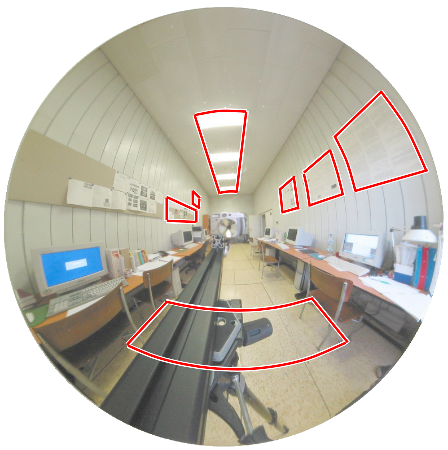
3D reconstruction - spherical mirror

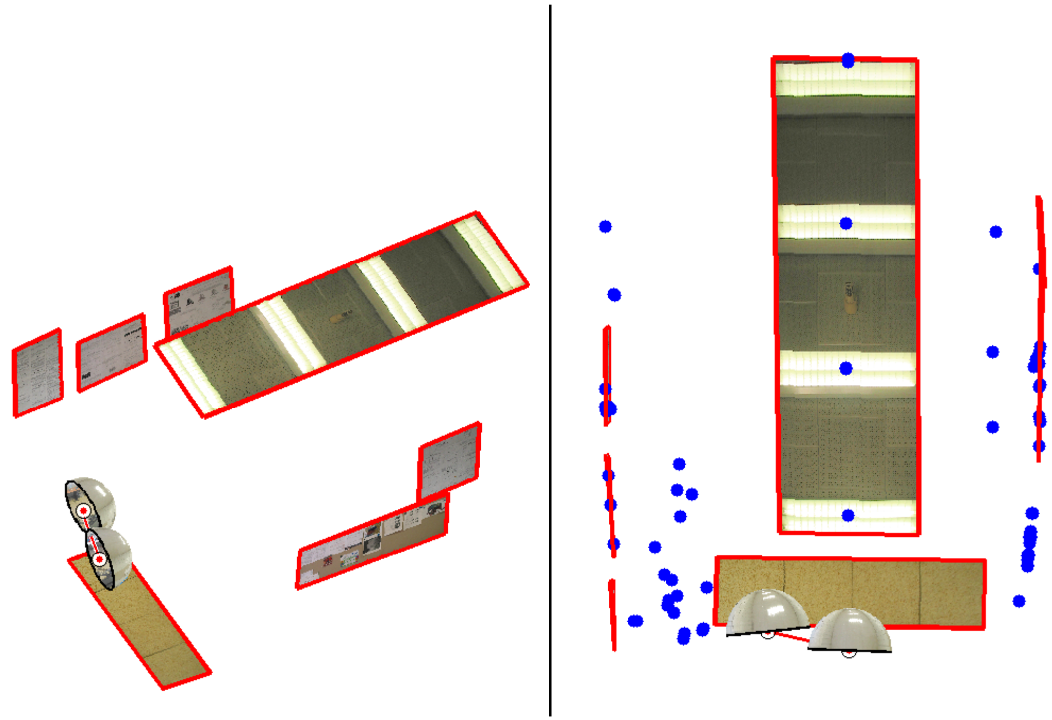


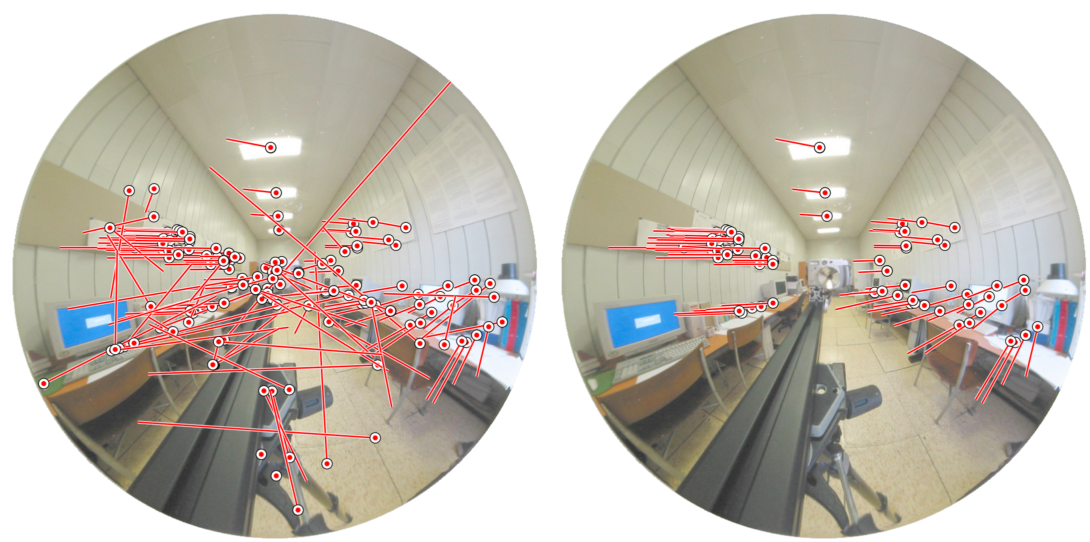




3D reconstruction - hyperbolic mirror







Conclusion

Main contribution:

- Epipolar geometry estimation and
- omnidirectional camera calibration
- by RANSAC with bucketing
- for very wide-angle ($> 180^\circ$) of view
- from point correspondences contaminated by outliers.
- 3D metric reconstruction from two or more uncalibrated central omnidirectional images.
- Models for non-central catadioptric cameras.
- 3D metric reconstruction from two uncalibrated non-central catadioptric images.

Conclusion

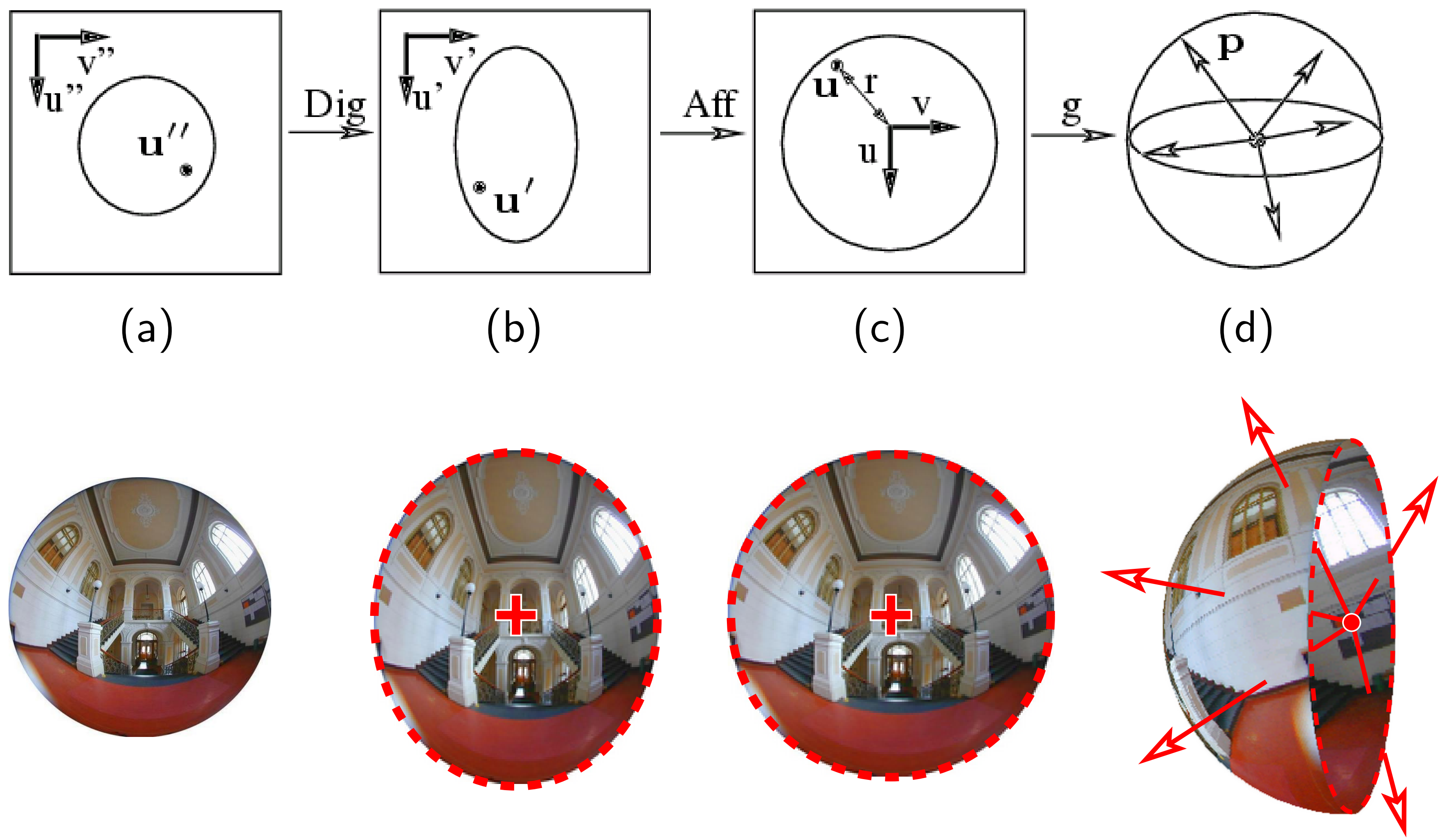
Main contribution:

- Epipolar geometry estimation and
- omnidirectional camera calibration
- by RANSAC with bucketing
- for very wide-angle ($> 180^\circ$) of view
- from point correspondences contaminated by outliers.
- 3D metric reconstruction from two or more uncalibrated central omnidirectional images.
- Models for non-central catadioptric cameras.
- 3D metric reconstruction from two uncalibrated non-central catadioptric images.

Remarks:

- It is the number of parameters, rather than the actual form of the non-linear function, what allows to formulate the calibration process as PEP
- Experiments show that
  - more complete 3D reconstruction from fewer omnidirectional images
  - large field of view → very stable results even without bundle adjustment
  - suitable model + linearization + PEP → solves large class of lenses and mirrors

Review of the full calibration process (back)



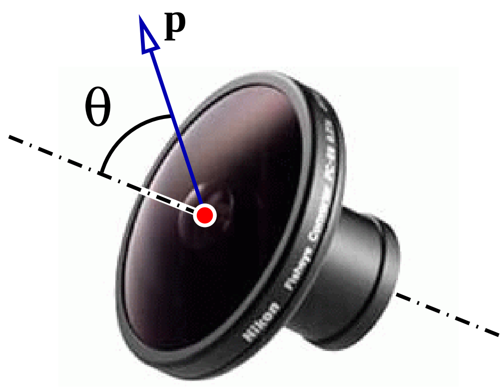
(a) – Image on the sensor plane (circular FOV)

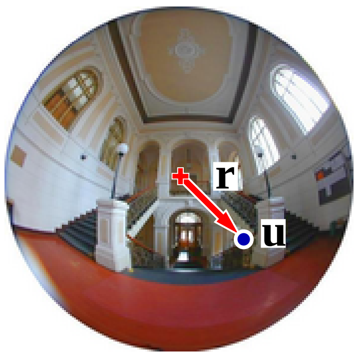
(b) – Digitized image (non-square pixel → elliptical FOV)

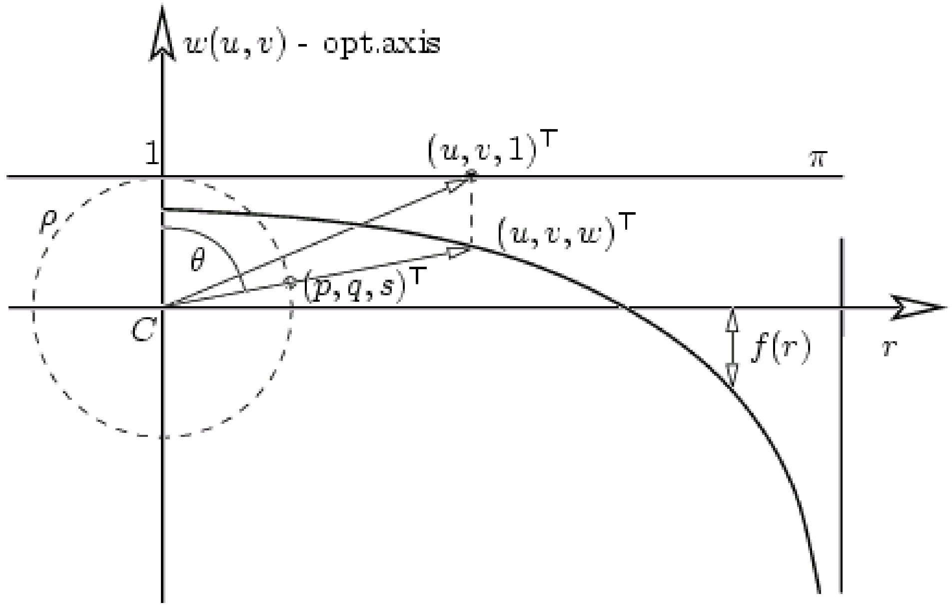
(c) – Precalibrated image (ellipse → circle, radial symmetry)

(d) – Full calibration (by epipolar geometry and QEP)

Non-linear mapping (back)







- Nonlinear camera models:

$$\theta = \frac{ar}{1+br^2}, \quad r = \frac{a}{b}\sin(b\theta), \ldots$$

- 3D vector corresponding to an image point:

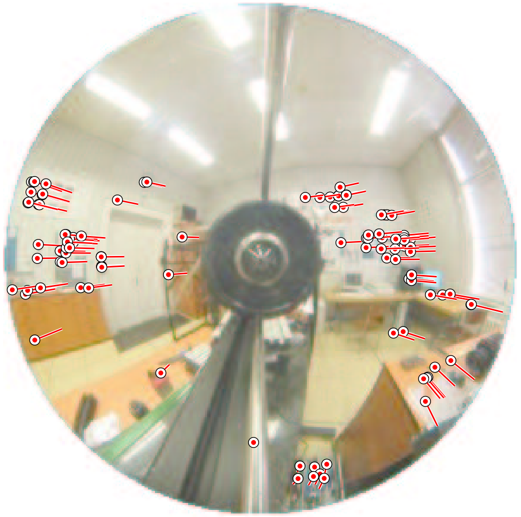
$$\mathbf{p} \simeq g(\mathbf{u}) = \begin{pmatrix} \mathbf{u} \\ w \end{pmatrix} = \begin{pmatrix} \mathbf{u} \\ f(\mathbf{u}, a, b) \end{pmatrix} = \begin{pmatrix} \mathbf{u} \\ \frac{r}{\tan\theta} \end{pmatrix} = \begin{pmatrix} \mathbf{u} \\ \frac{r}{\tan \frac{ar}{1+br^2}} \end{pmatrix}$$

Finding correspondences (back)

Pair of images with regions detected by Matas & Chum & Urban & Pajdla BMVC 2002

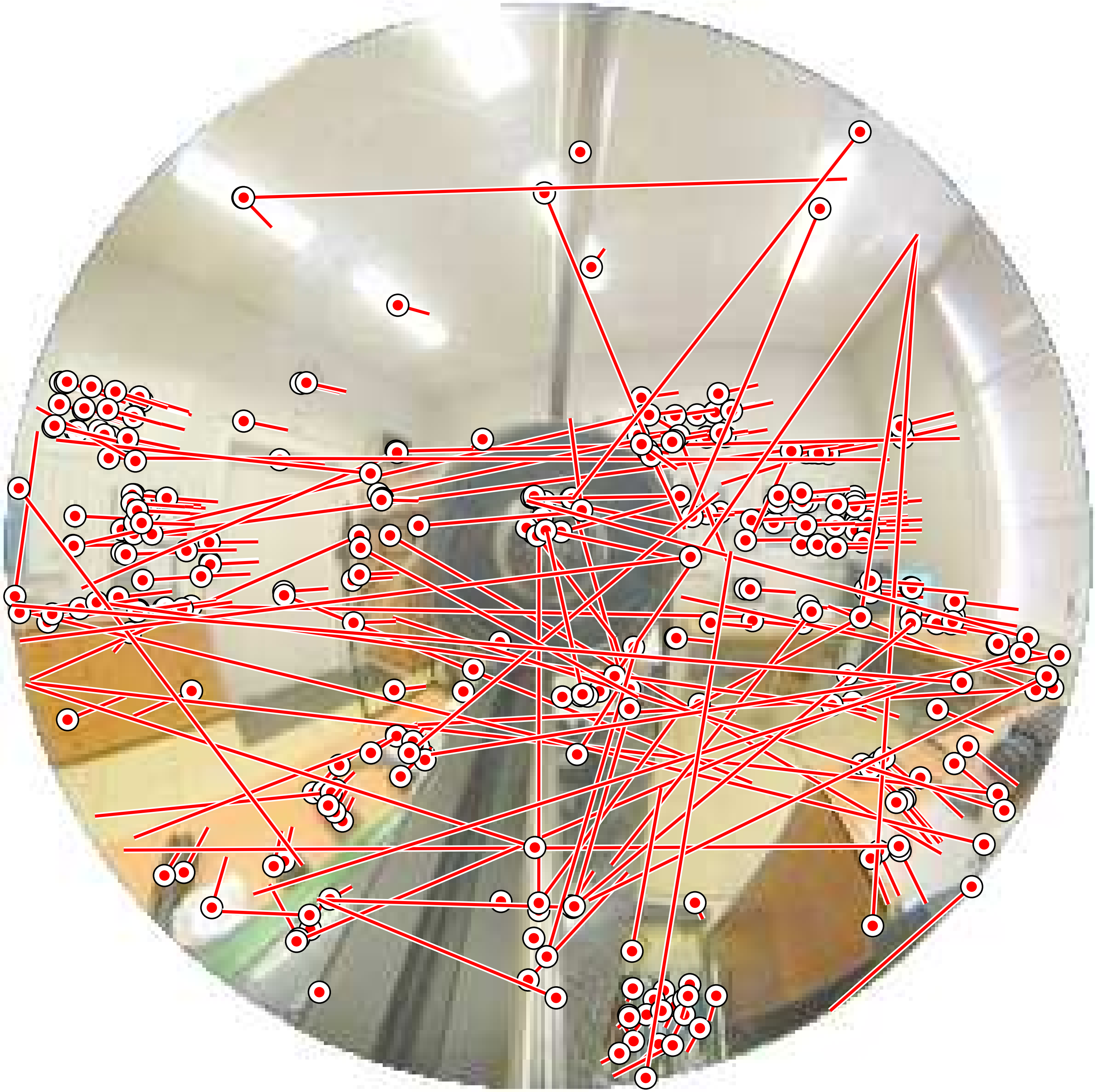
Tentative correspondences using similarity (Matas et al BMVC 2002) (many outliers)

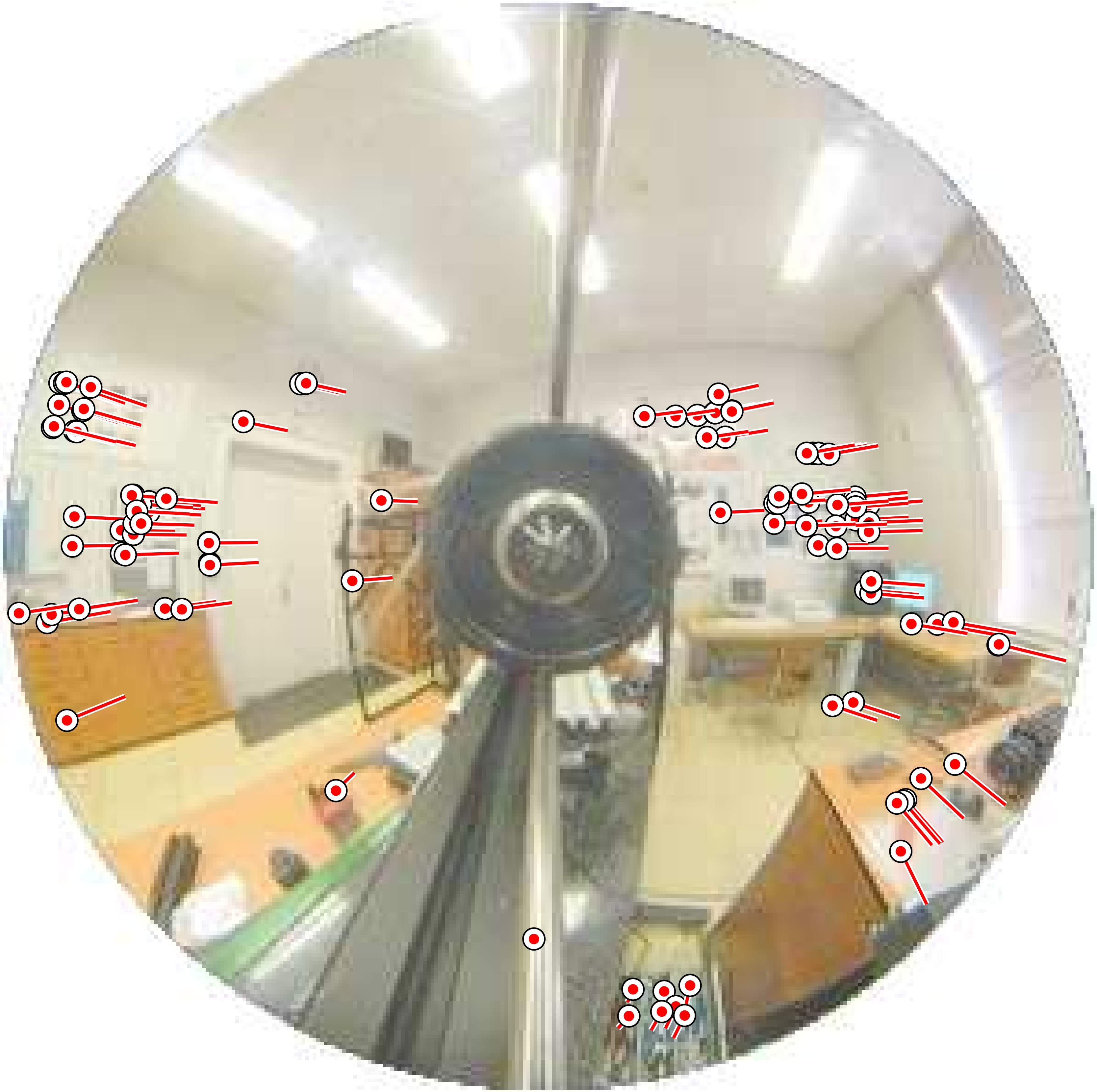


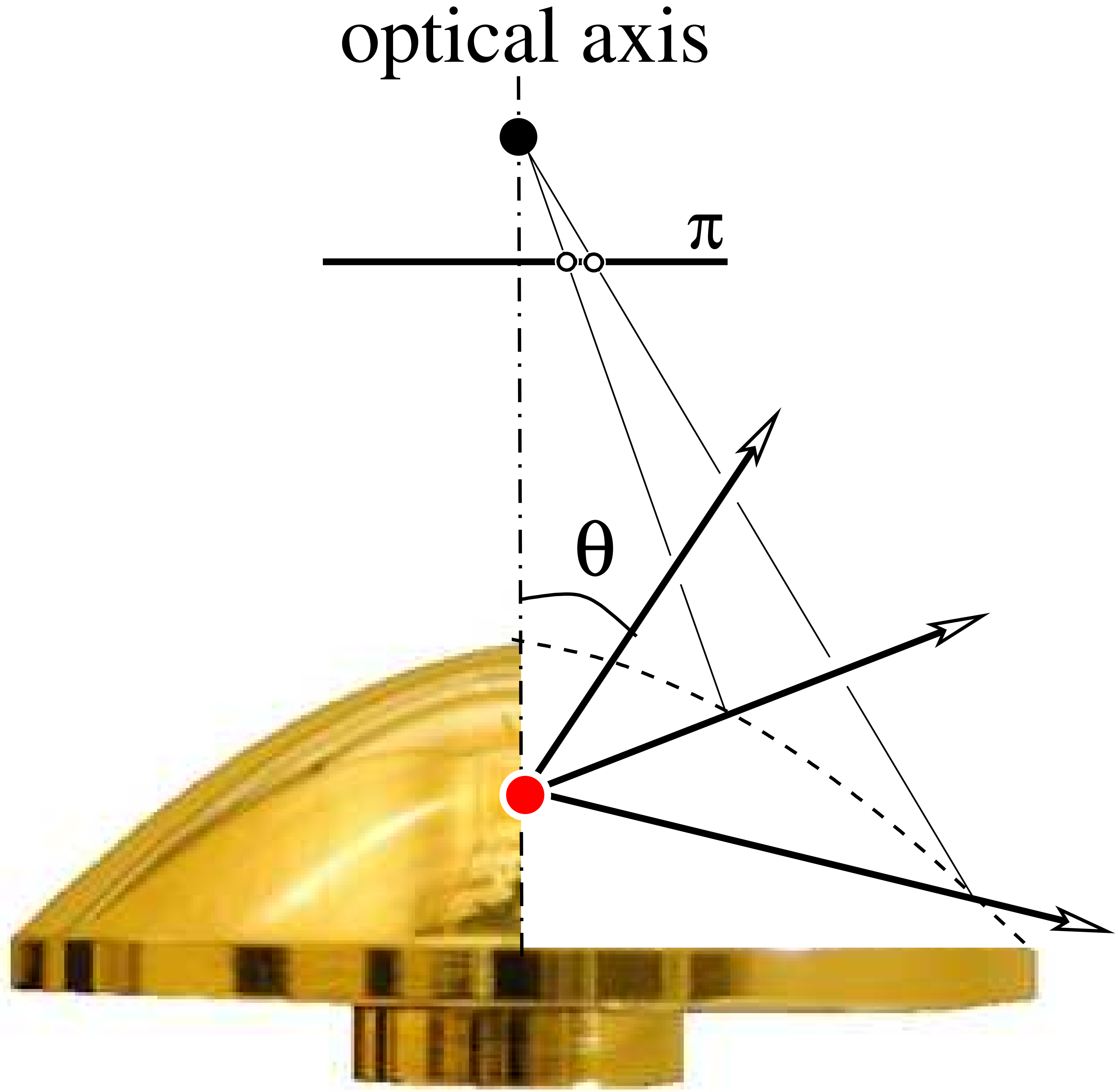
Inliers satisfying epipolar geometry of para-catadioptric cameras (Micusik & Pajdla ACCV 2004) m p

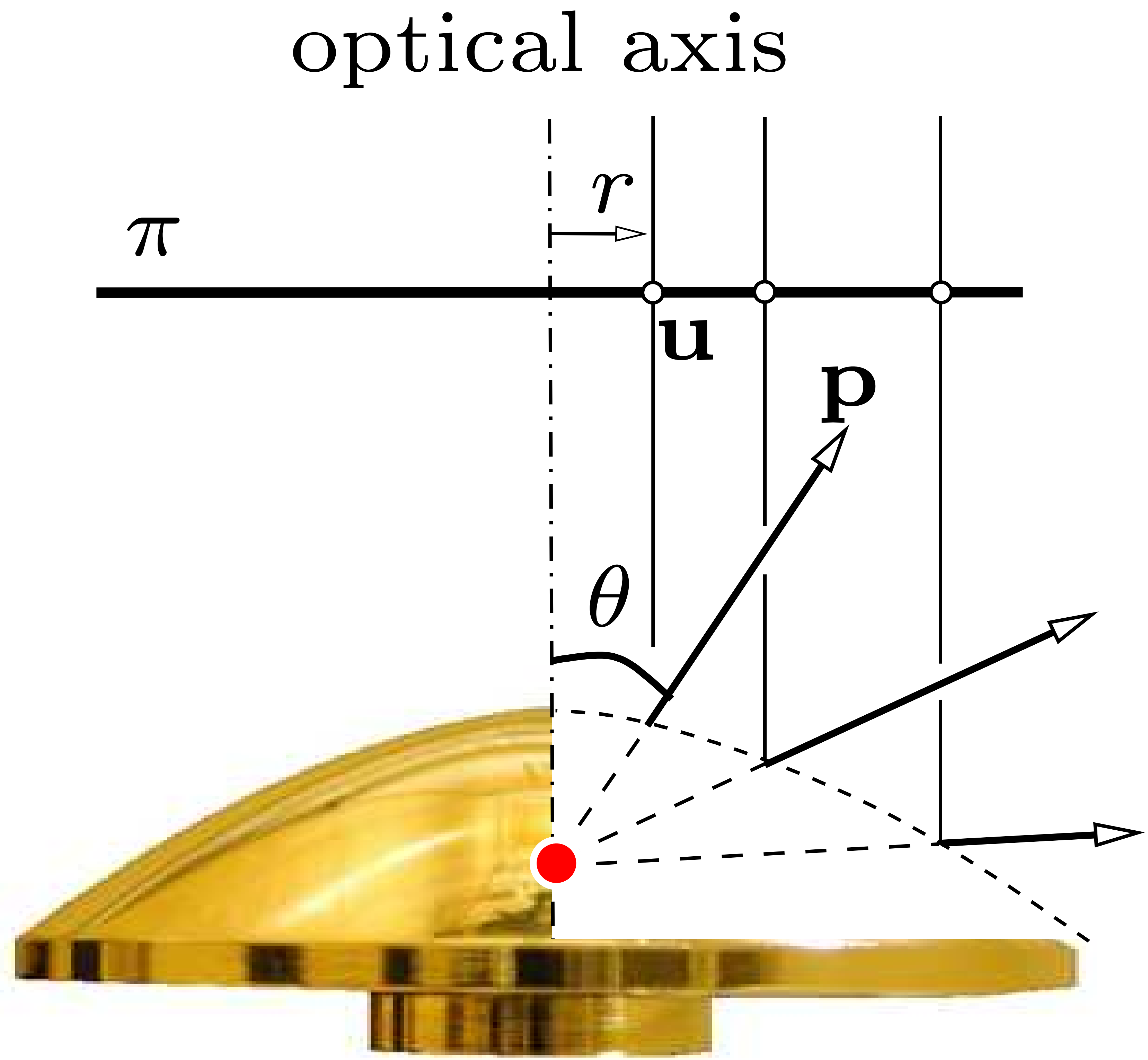

Nikon
DIGITAL CAMERA
COOLPIX
950

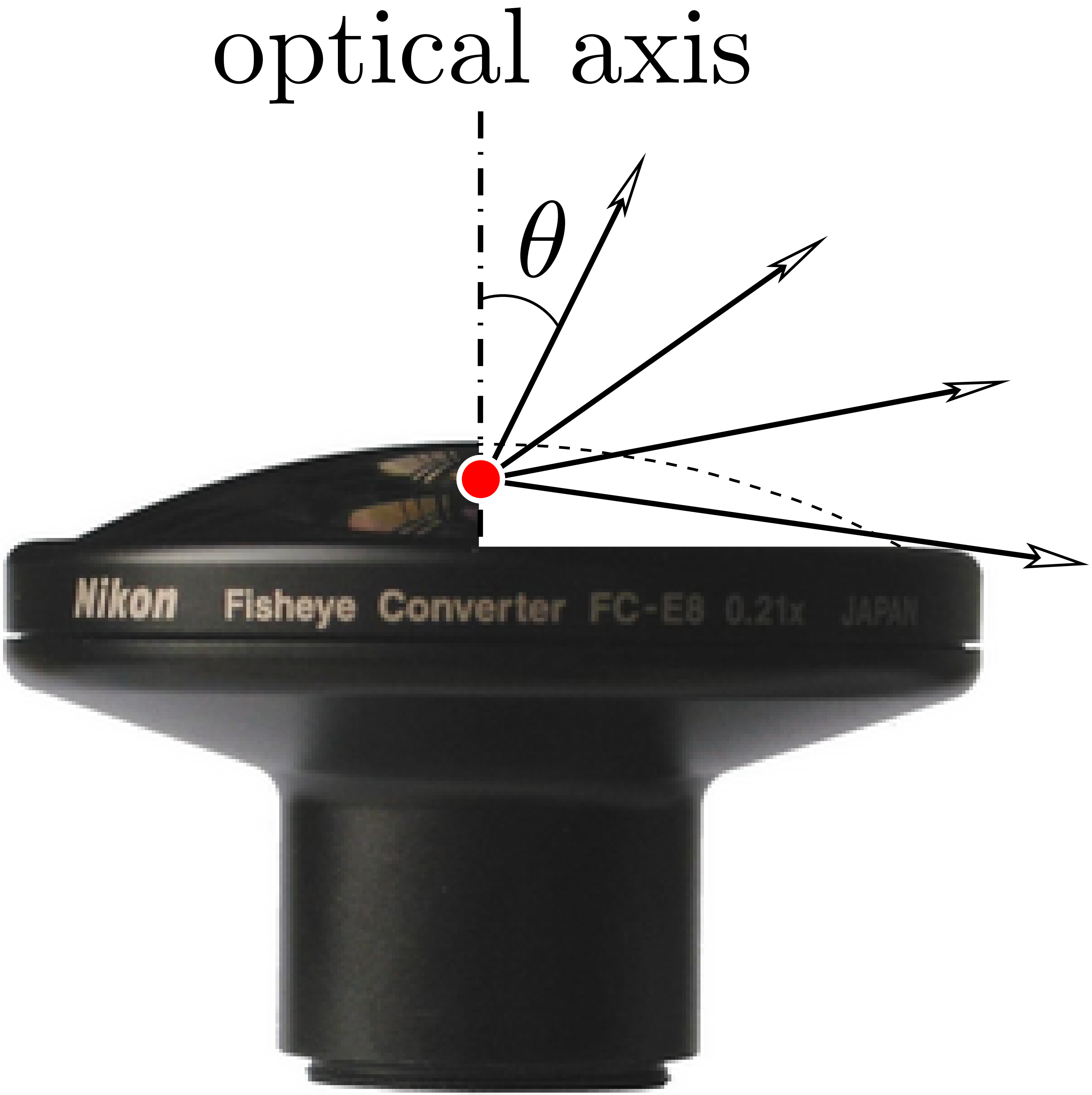

Canon

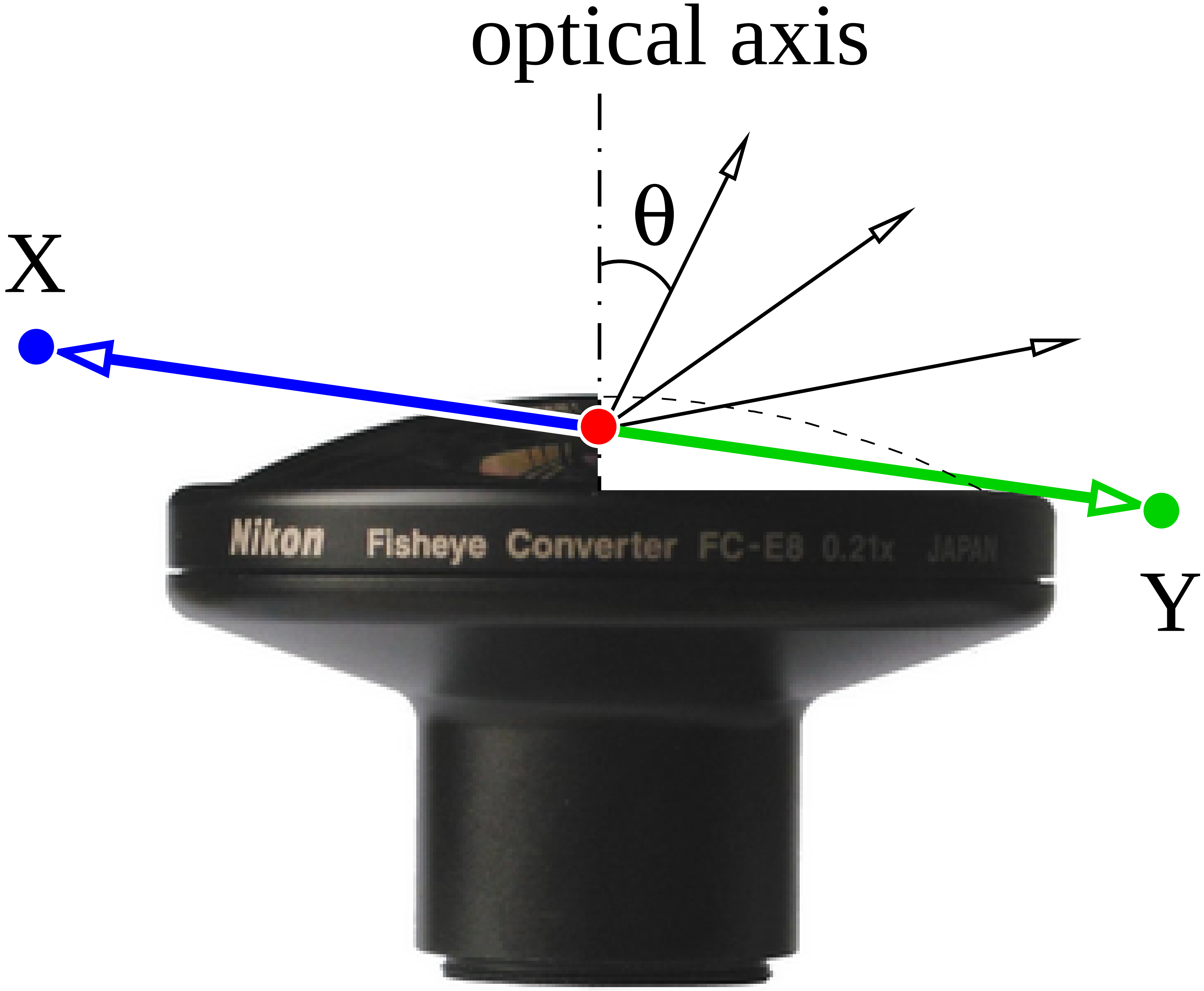


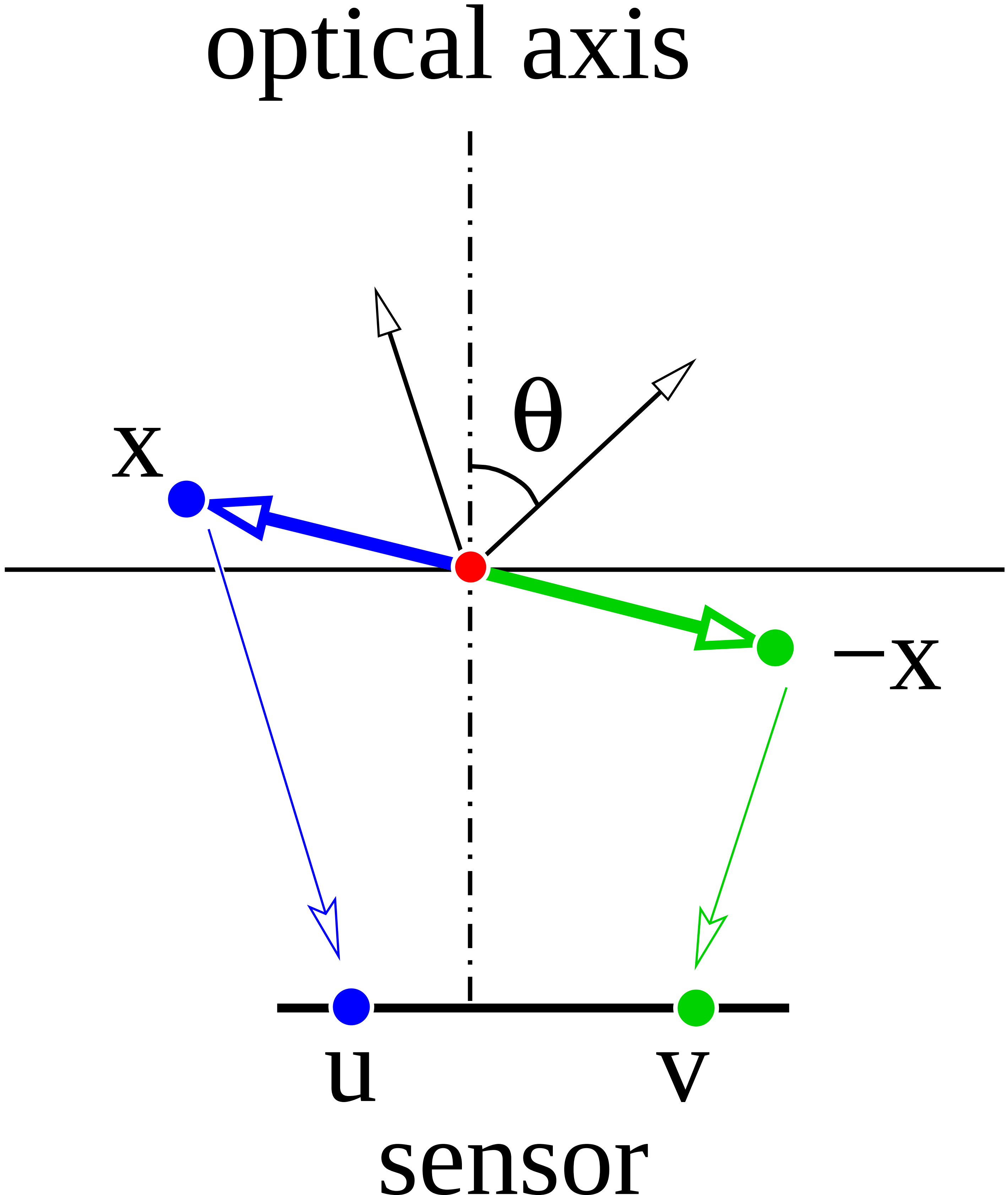


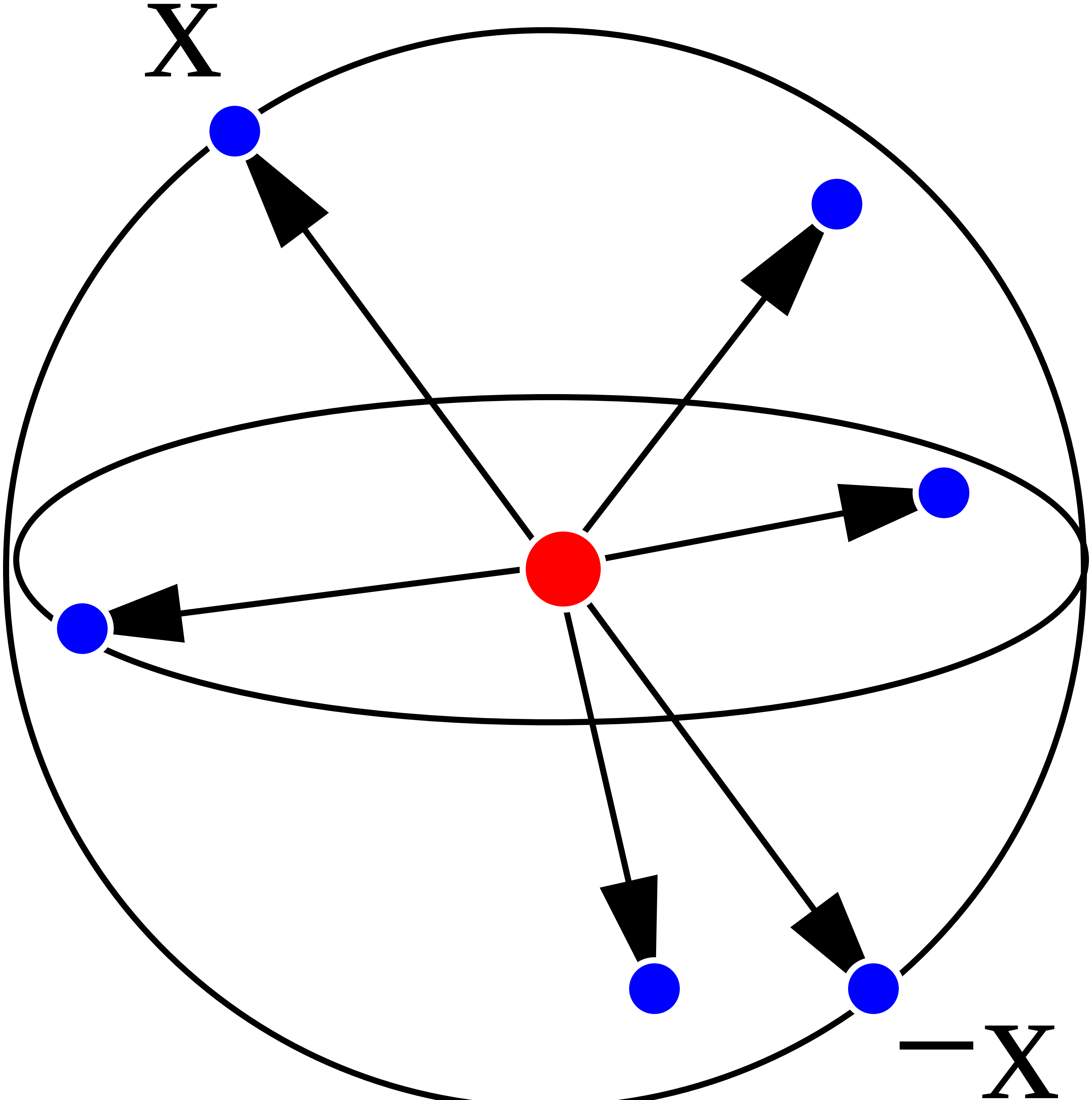

optical axis
π
θ

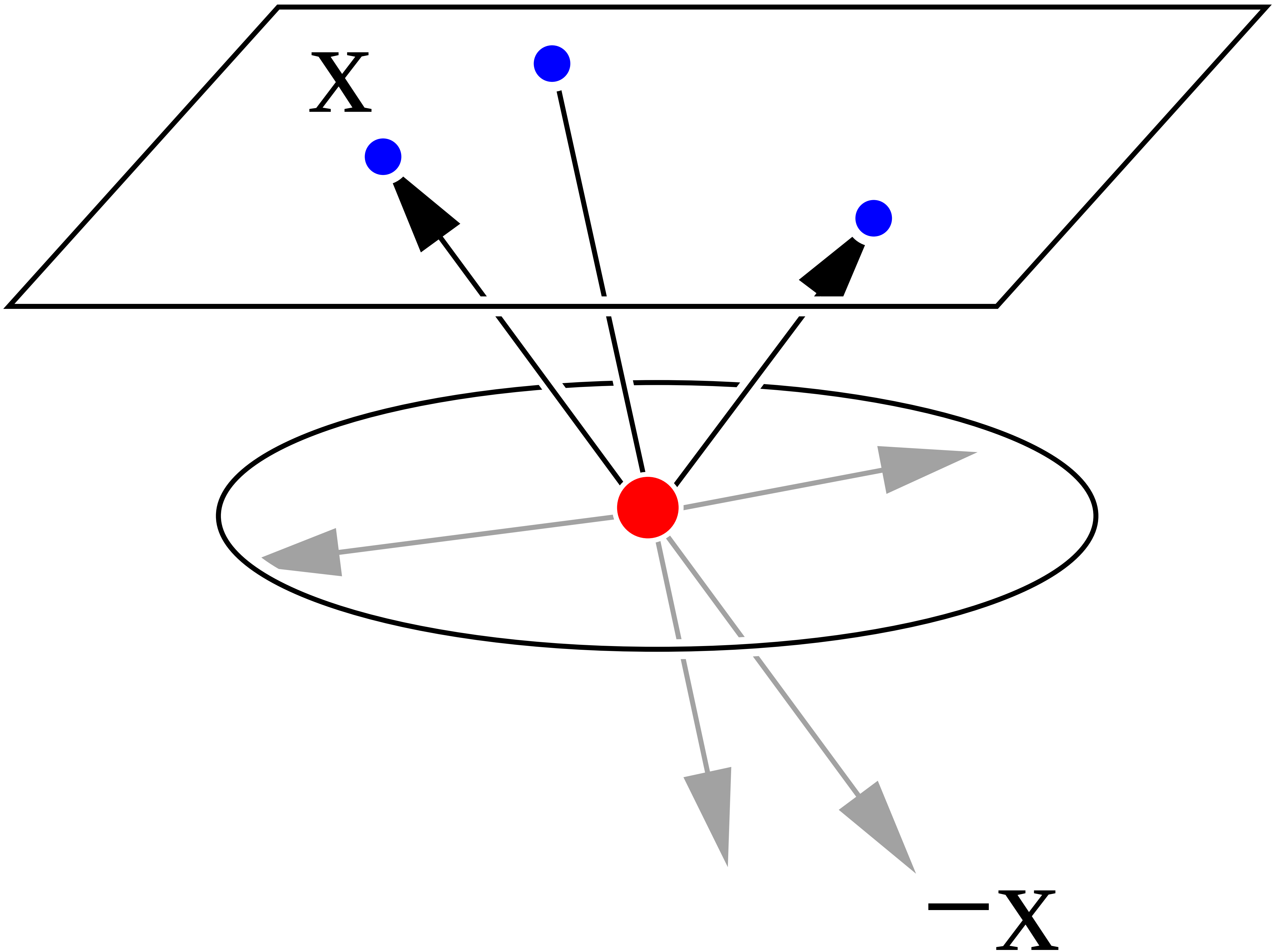

optical axis
r
π
$\mathbf{u}$
$\mathbf{p}$
θ


optical axis
θ
Nikon
Fisheye Converter FC-E8 0.21x JAPAN

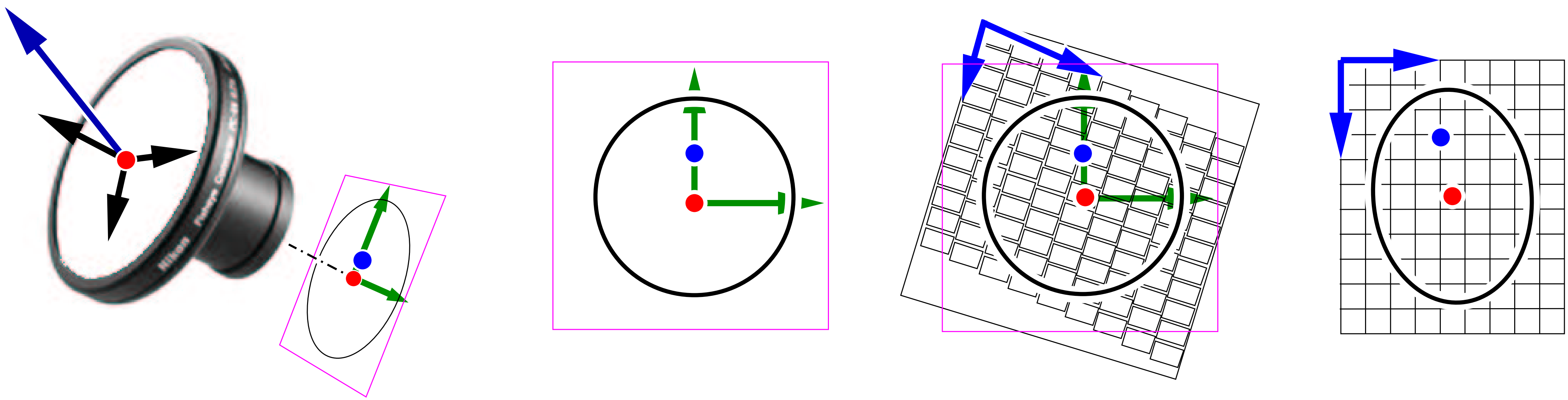

optical axis
θ
X
Y
Nikon Fisheye Converter FC-E8 0.21x JAPAN

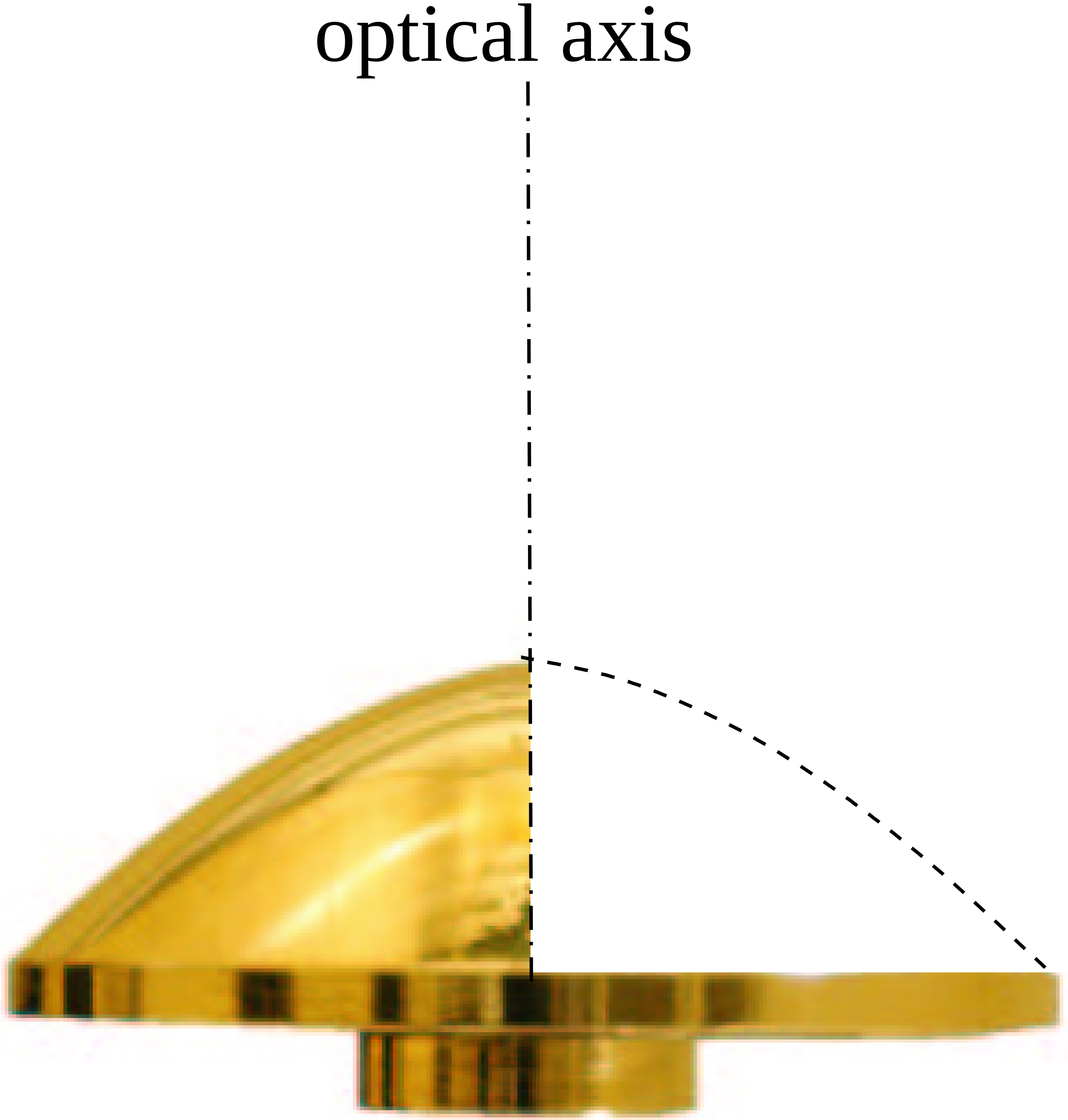

optical axis
θ
x
−x
u
v
sensor


X
−X

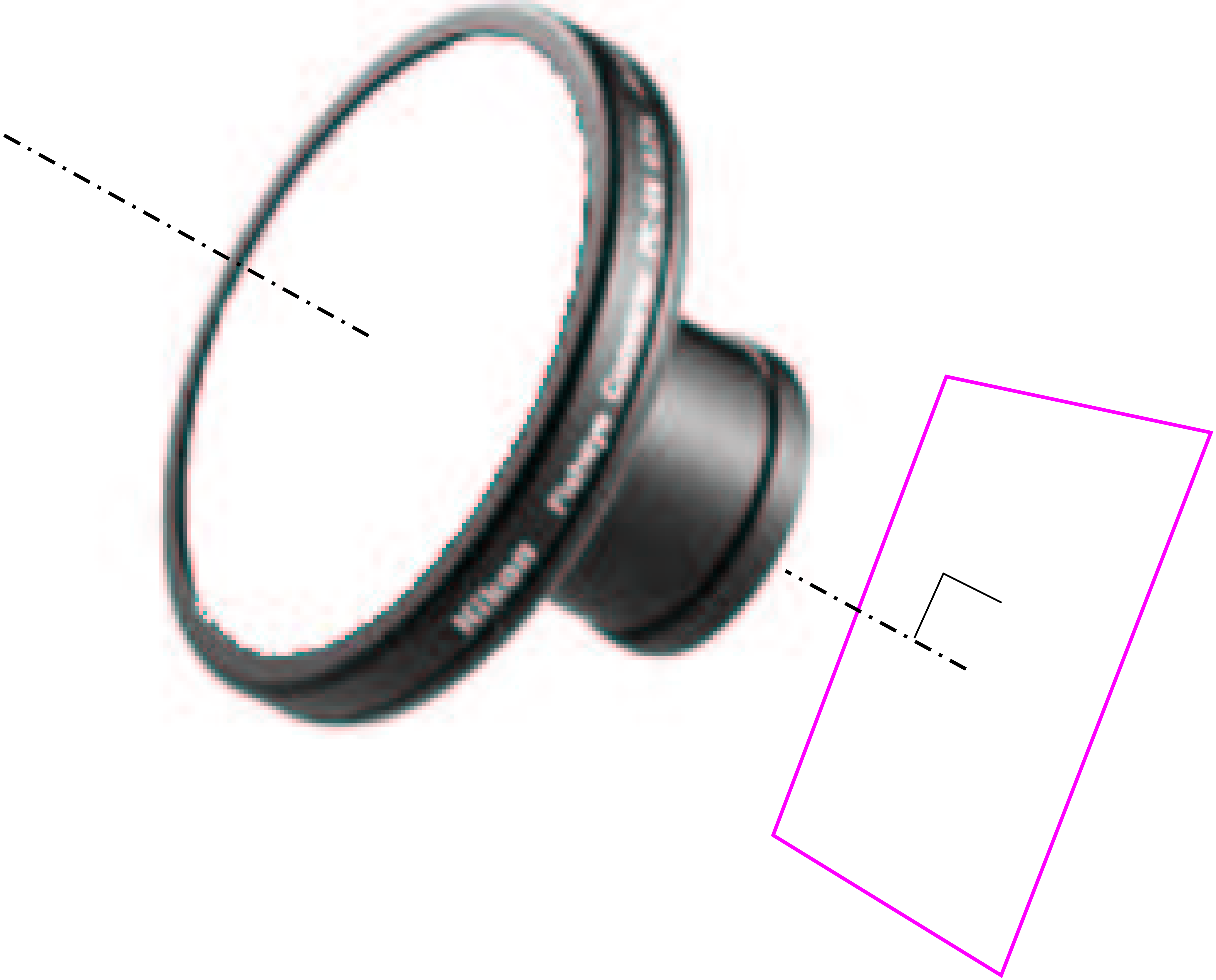


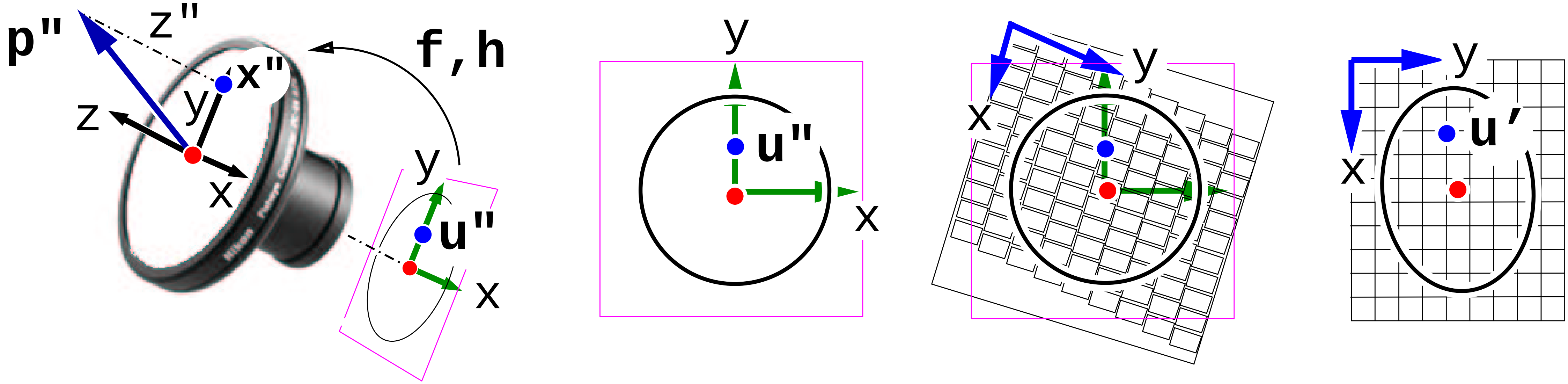
X
−X

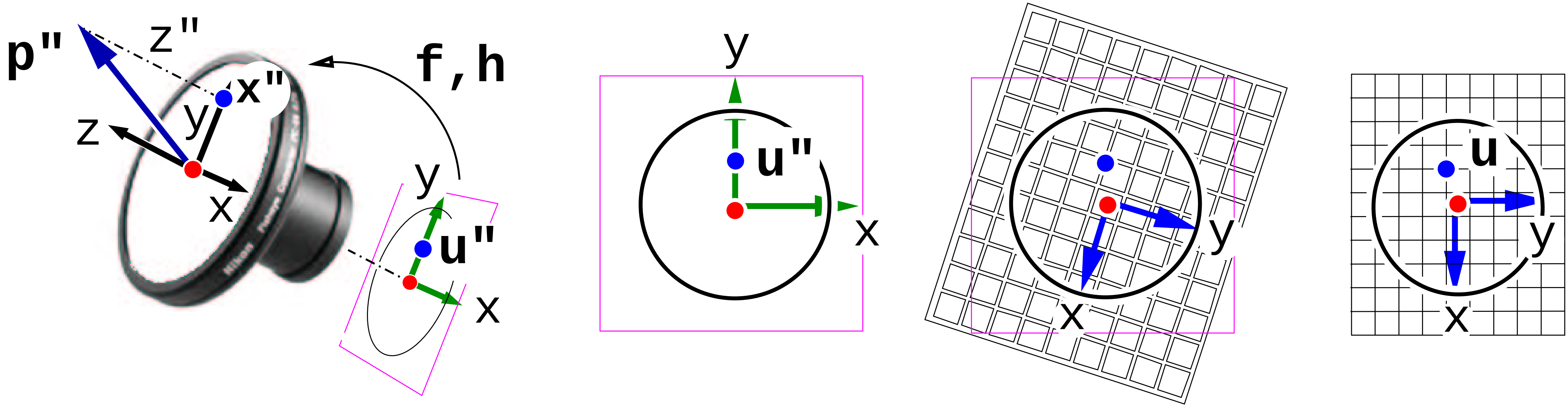



optical axis


optical axis
Nikon
Fisheye Converter




p"
z"
x"
y
z
x
f,h
y
u"
x
y
u"
x
y
x
y
u′
x



p"
z"
x"
y
z
x
f, h
y
u"
x
y
u"
x
y
x
u
y
x


PULNiX
PROGRESSIVE SCAN
Nikon


Nikon
u


r
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p
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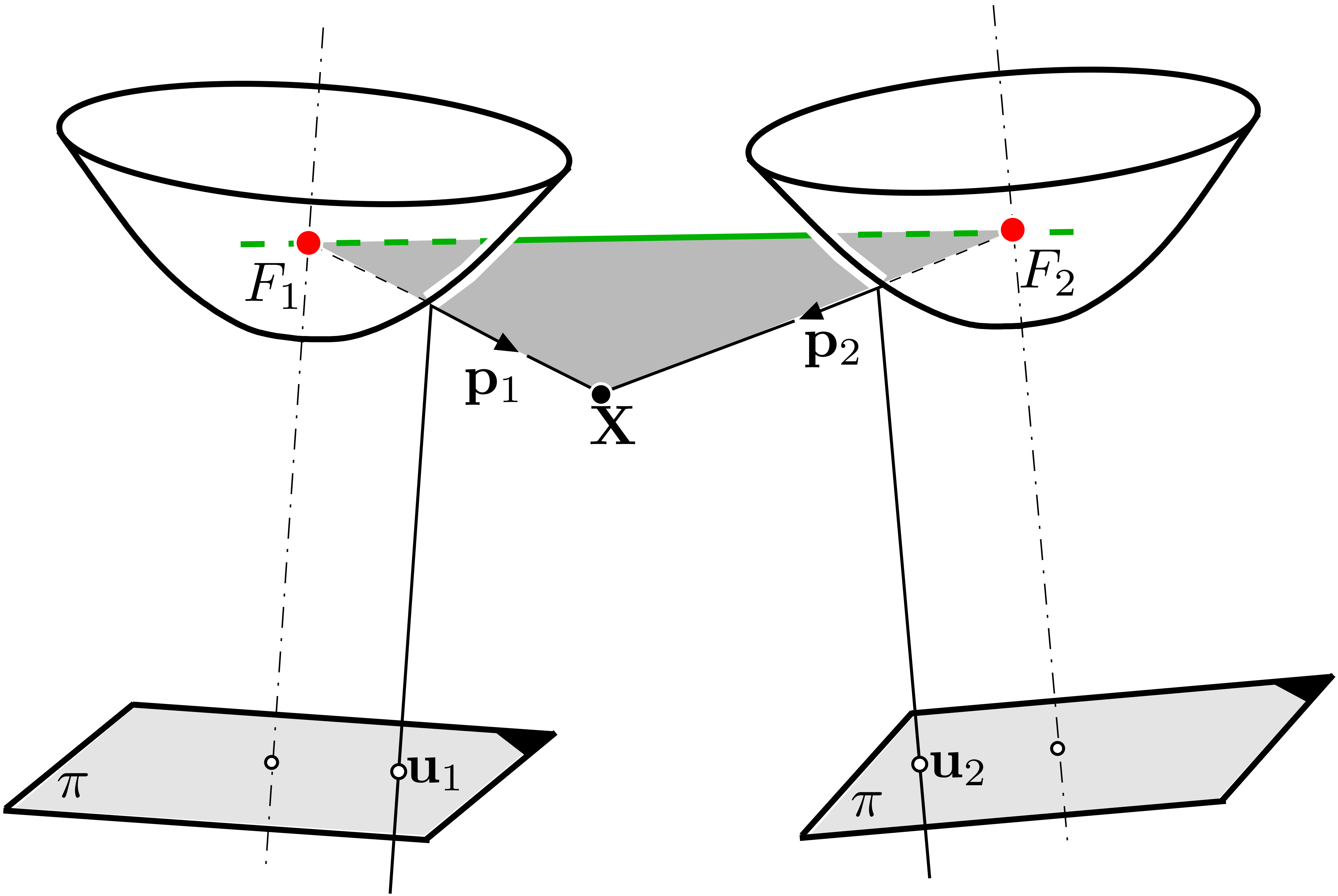
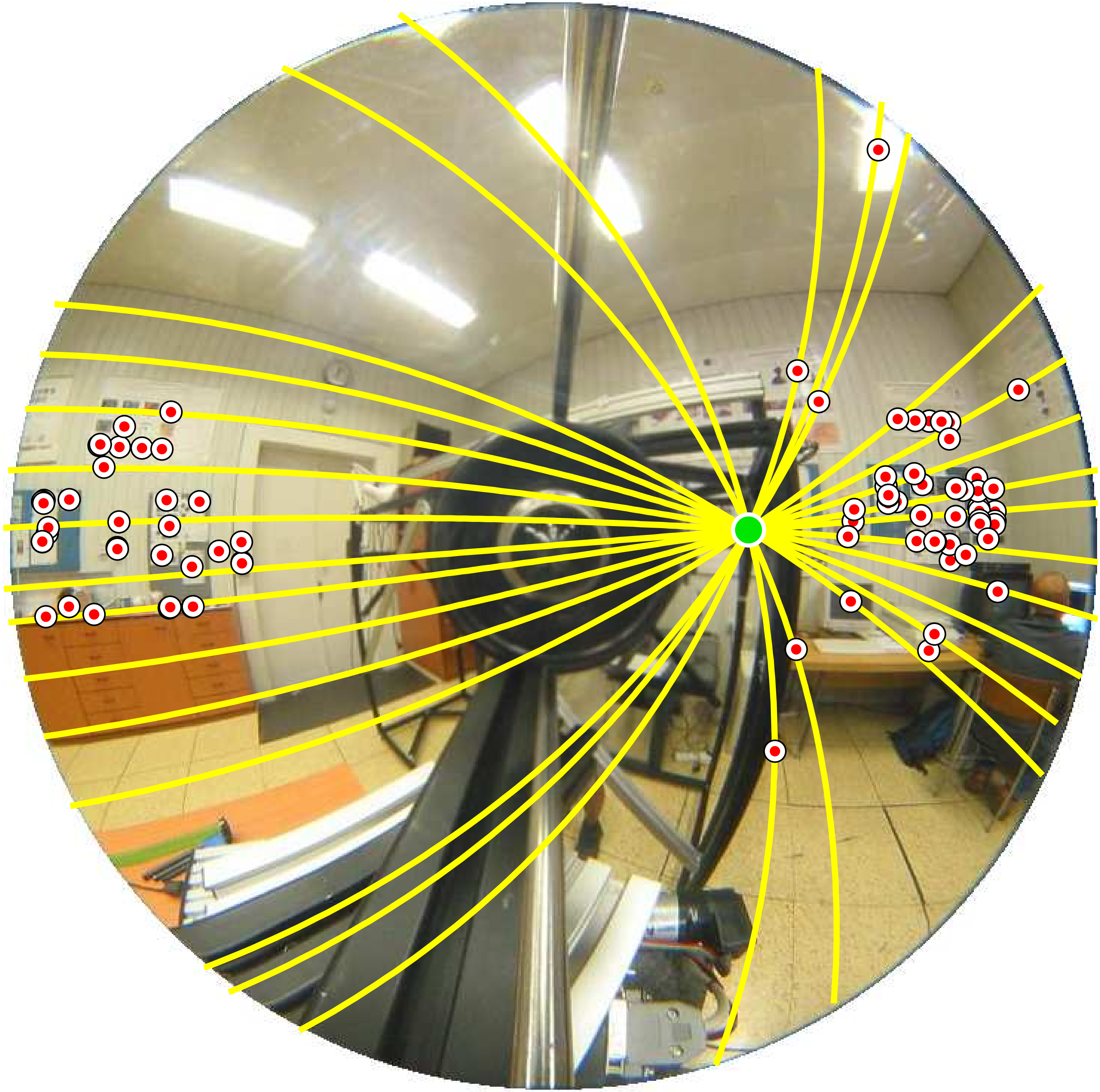
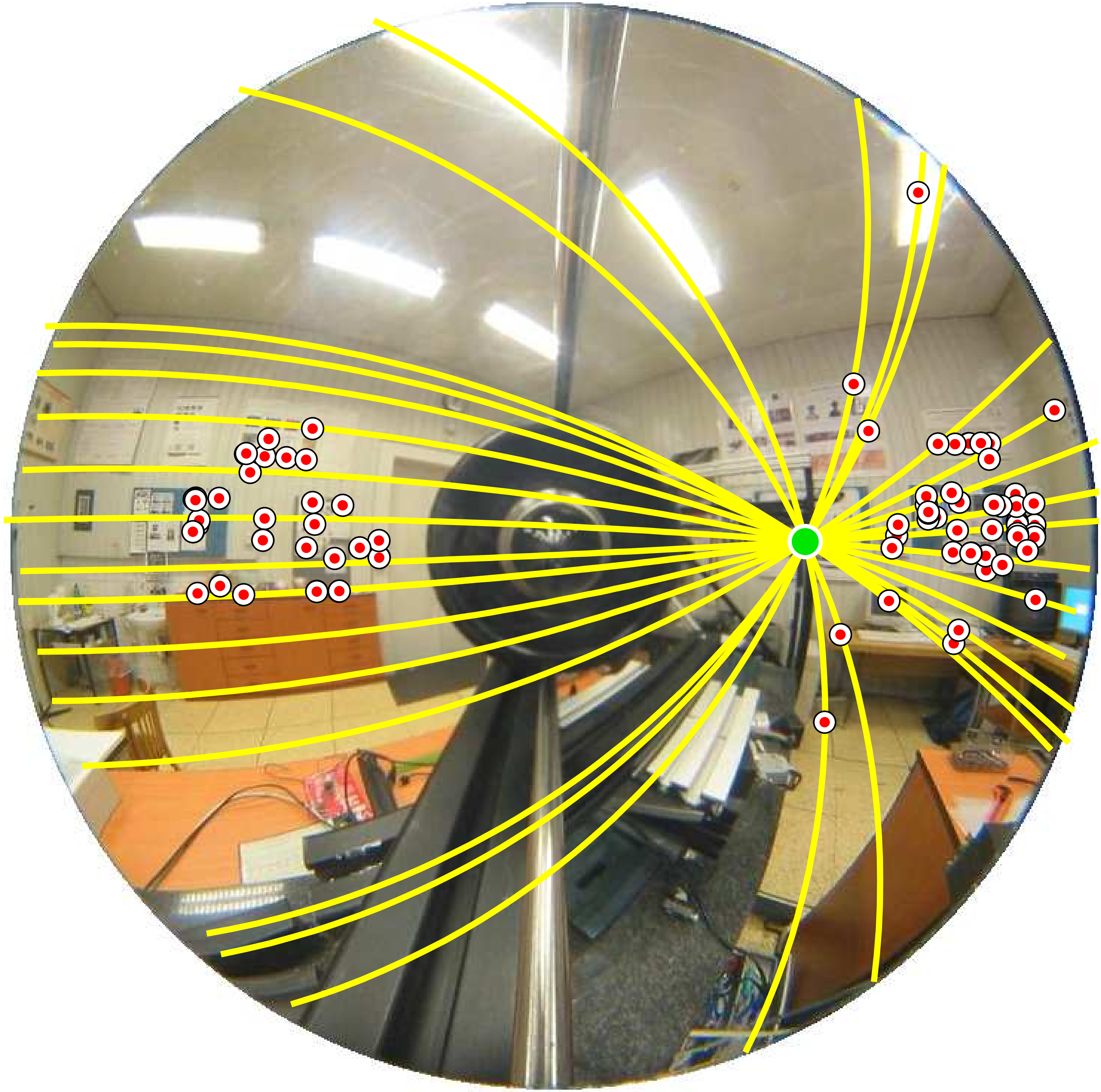
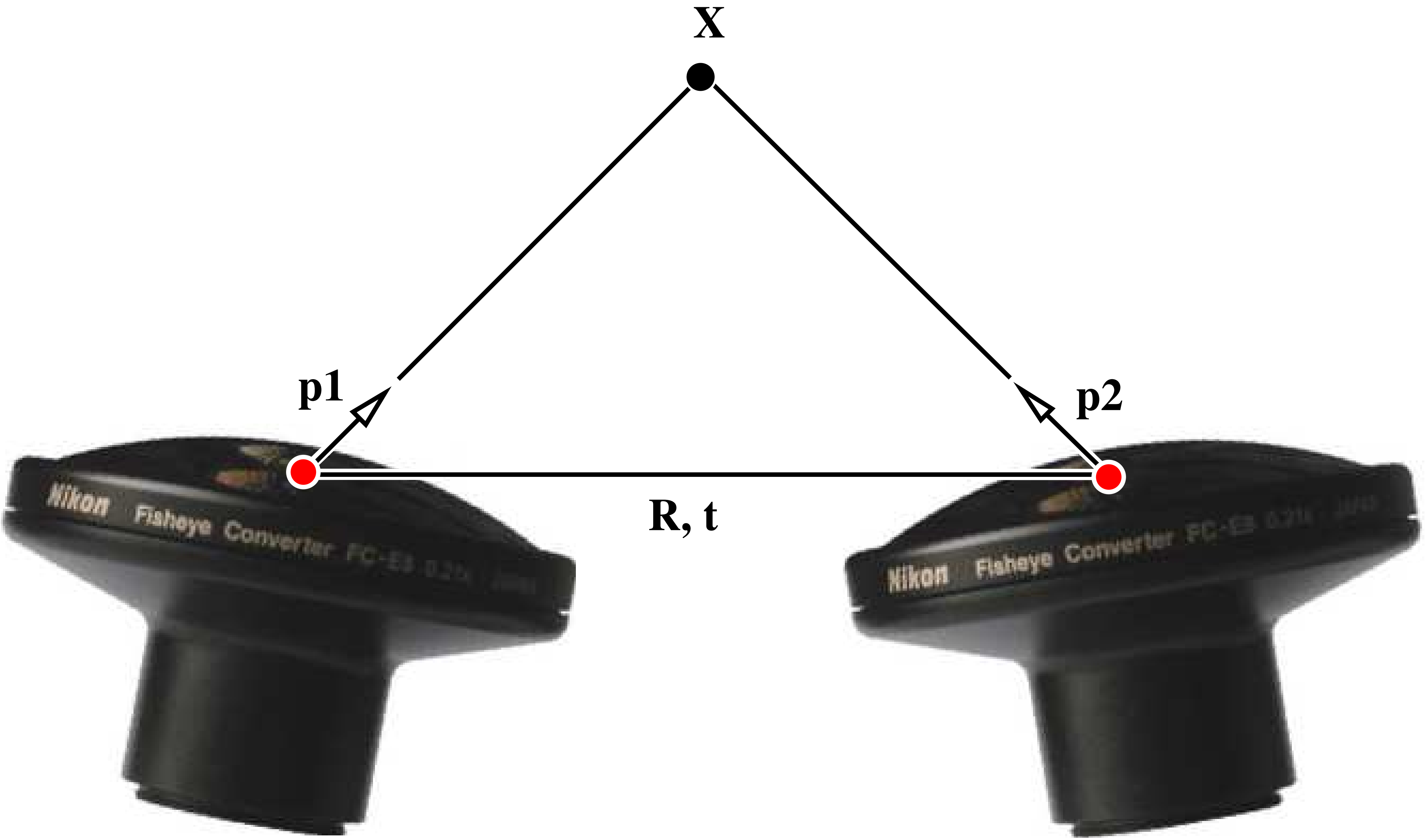
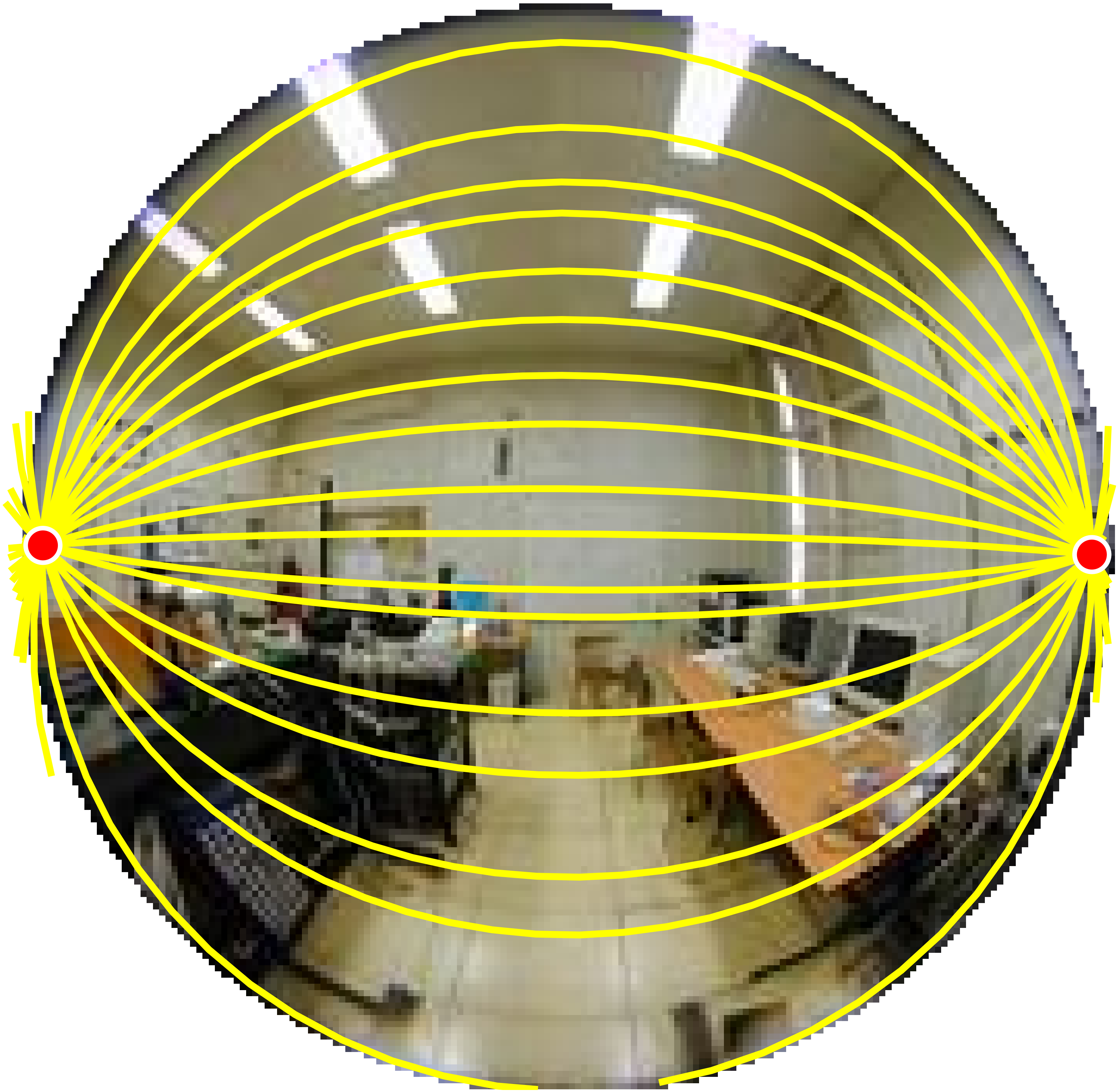


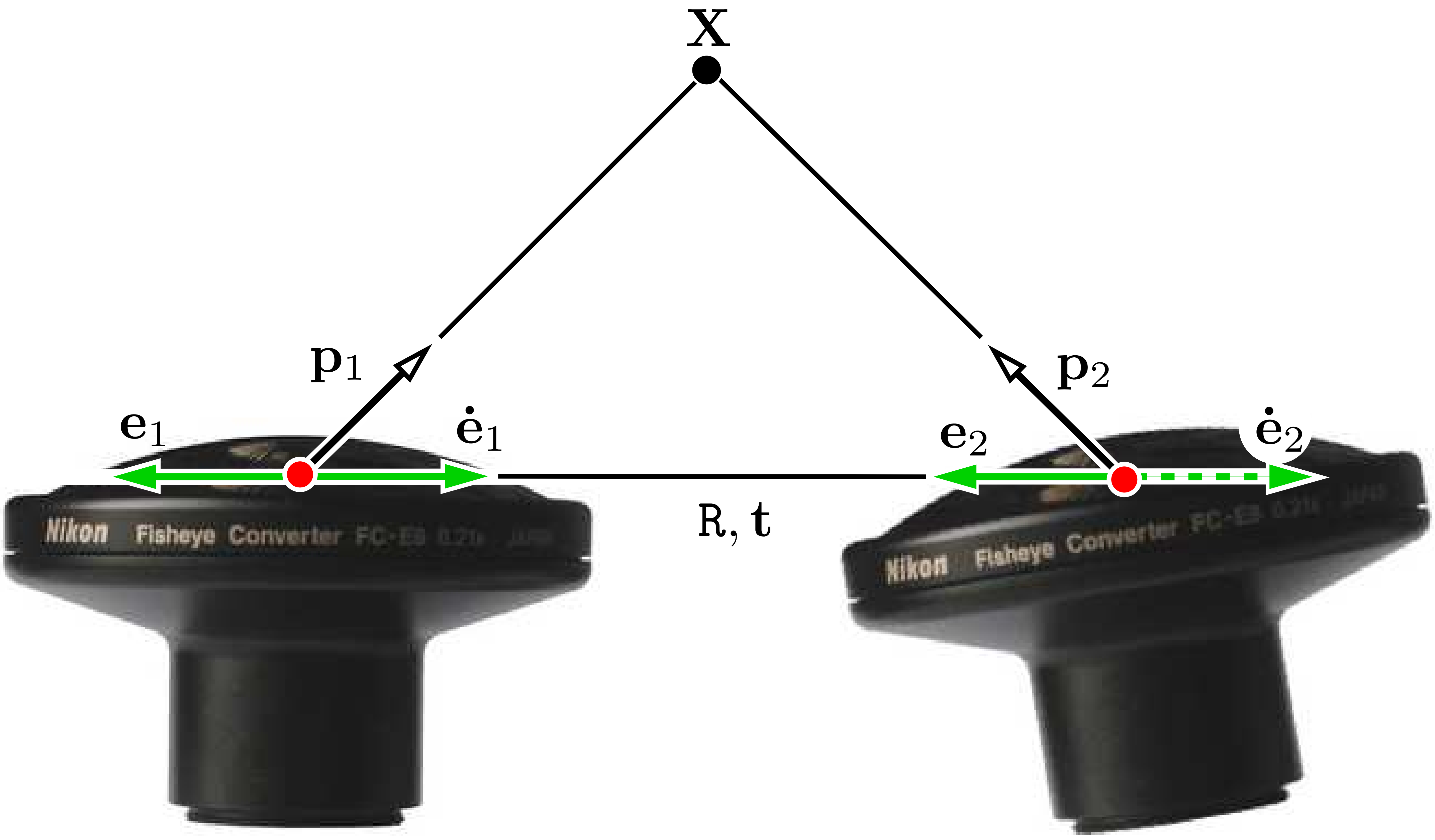
F_1
F_2
$\mathbf{p}_1$
$\mathbf{p}_2$
$\mathbf{X}$
$\mathbf{u}_1$
$\mathbf{u}_2$
π
π



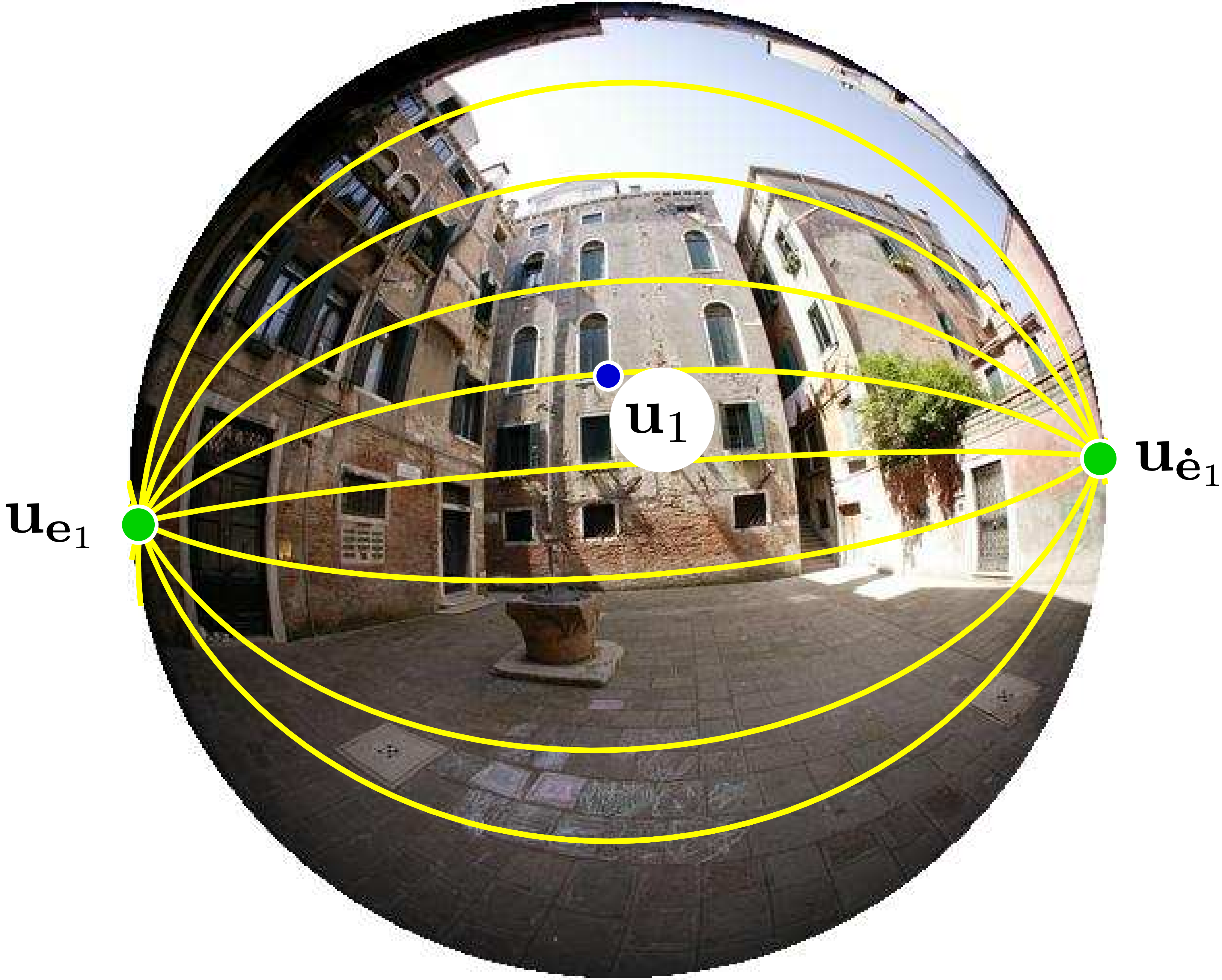


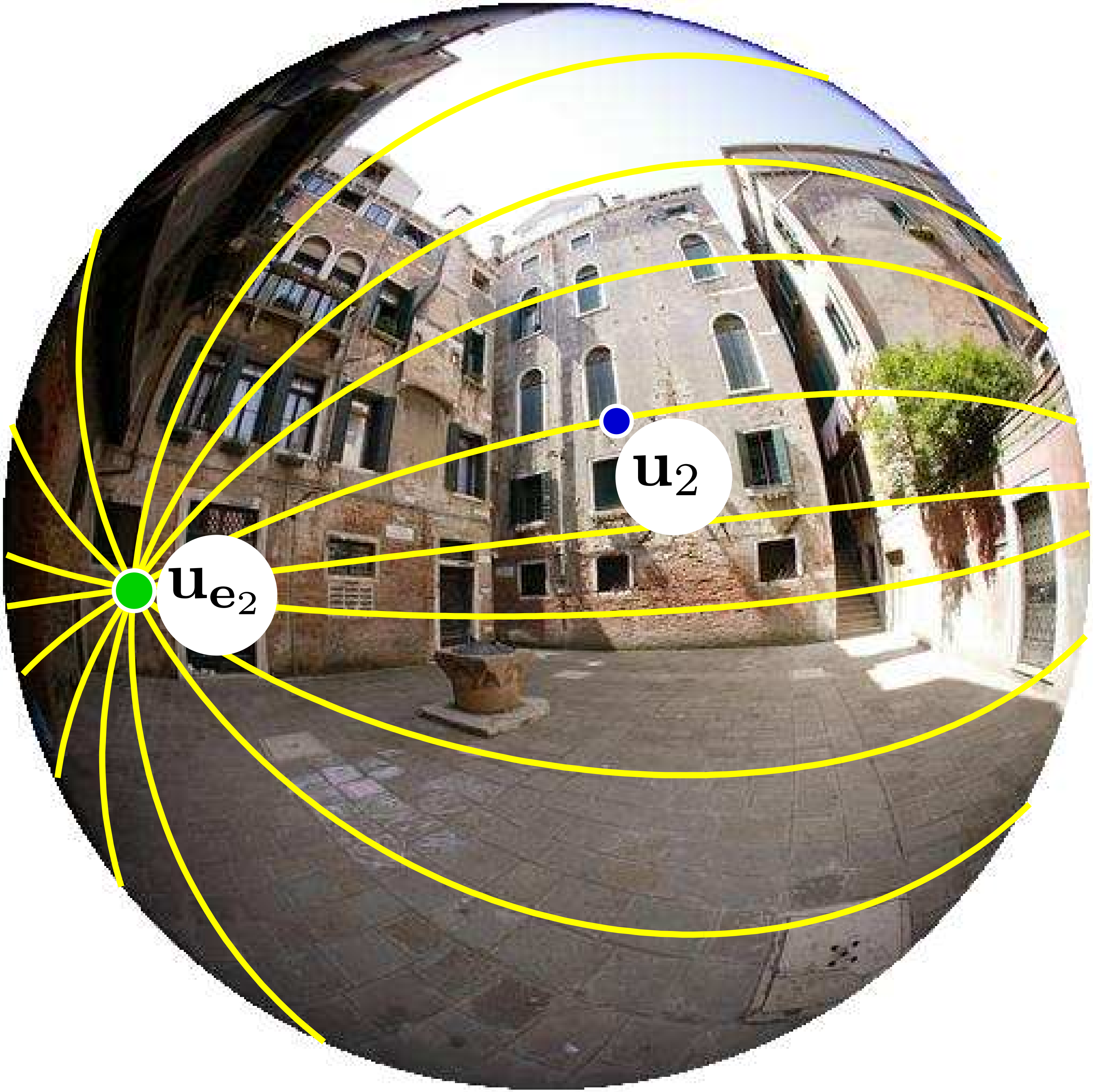

X
p1
p2
R, t
Nikon Fisheye Converter
Nikon Fisheye Converter



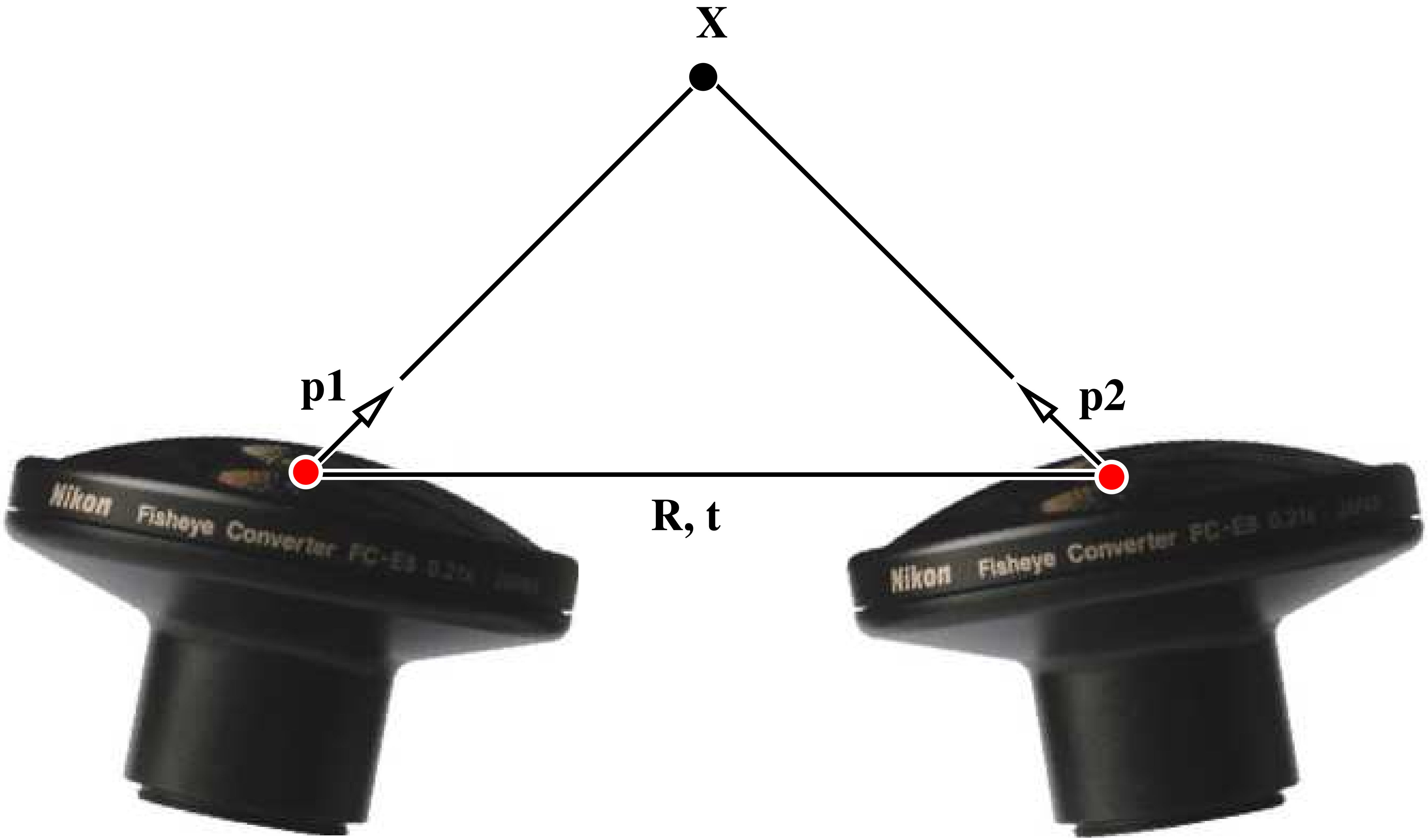


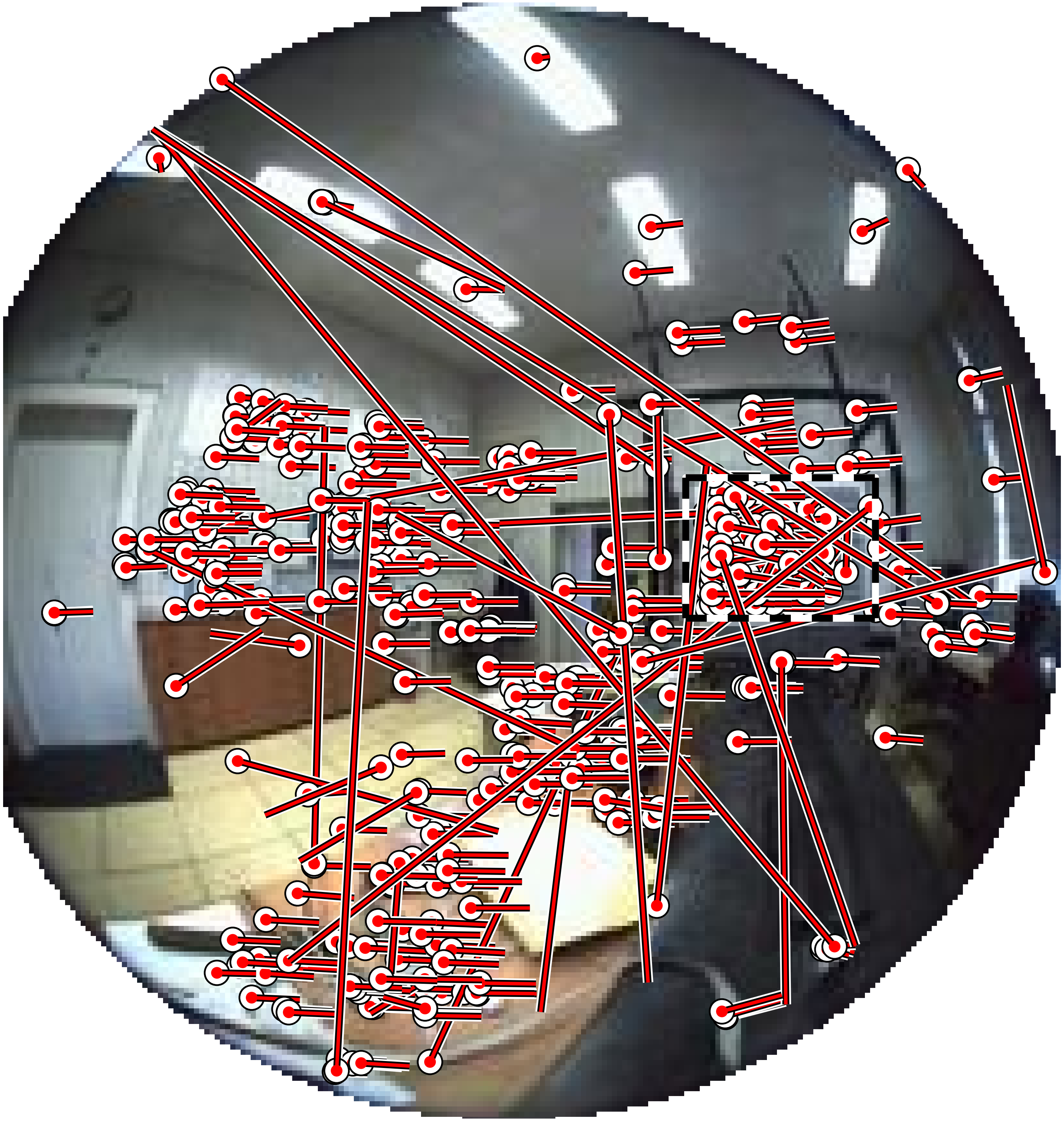
$\mathbf{X}$
$\mathbf{p}_1$
$\mathbf{p}_2$
$\mathbf{e}_1$
$\dot{\mathbf{e}}_1$
$\mathbf{e}_2$
$\dot{\mathbf{e}}_2$
$\mathtt{R}, \mathbf{t}$
Nikon Fisheye Converter FC-E8
Nikon Fisheye Converter FC-E8

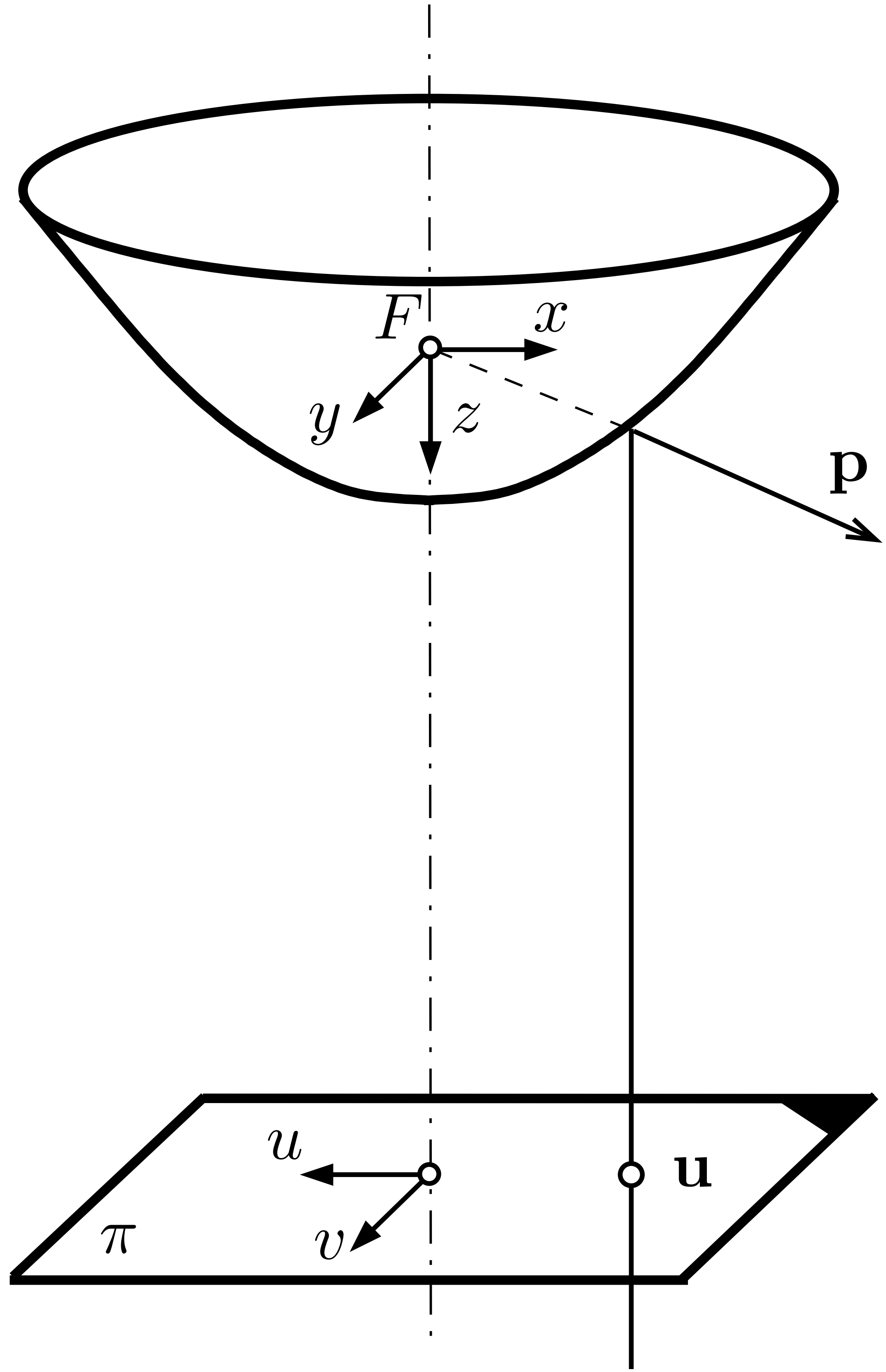

$\mathbf{u}_1$
$\mathbf{u}_{\dot{\mathbf{e}}_1}$
$\mathbf{u}_{\mathbf{e}_1}$



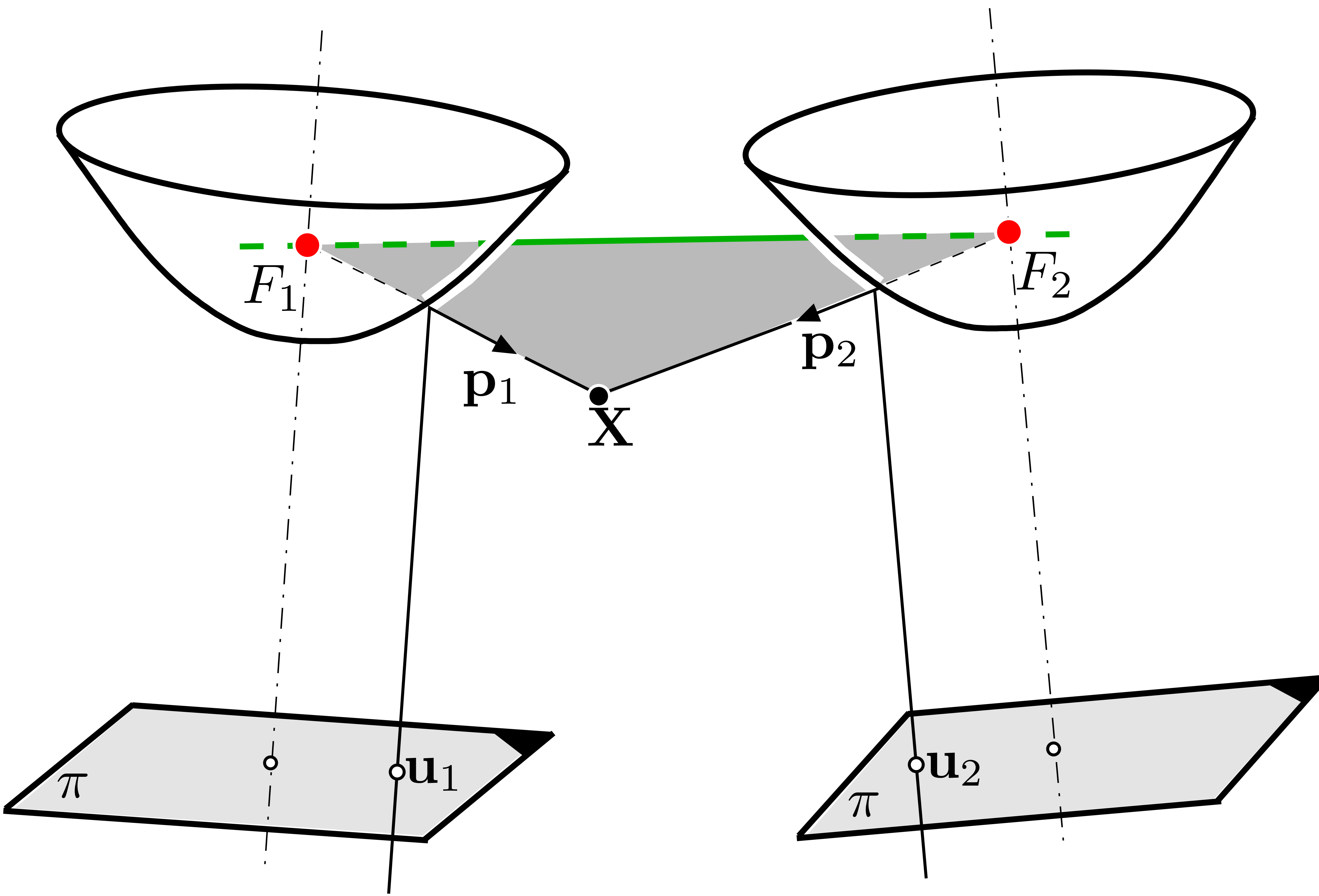
$\mathbf{u}_2$
$\mathbf{u}_{\mathbf{e}_2}$


X
p1
p2
R, t
Nikon Fisheye Converter
Nikon Fisheye Converter

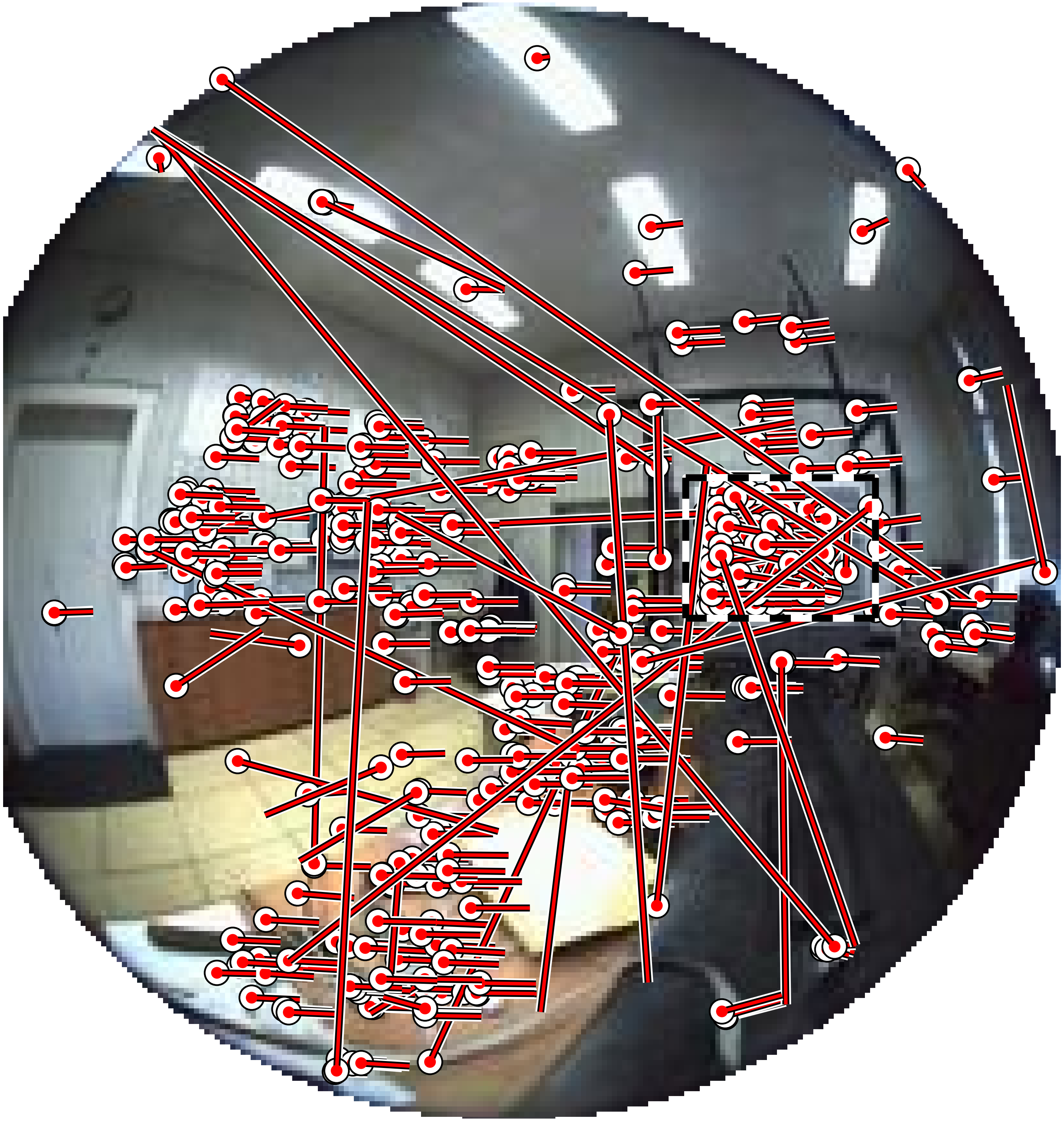


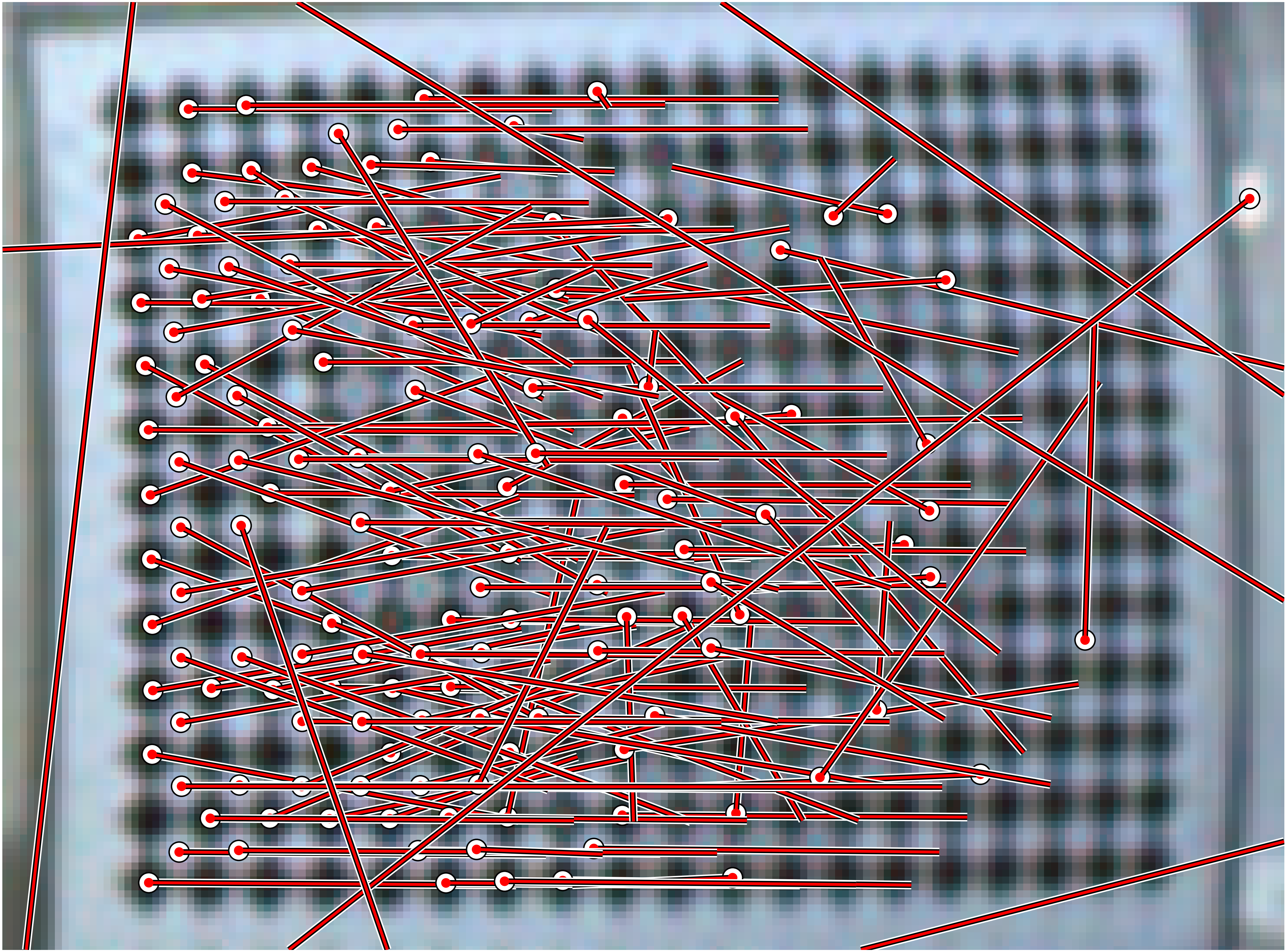


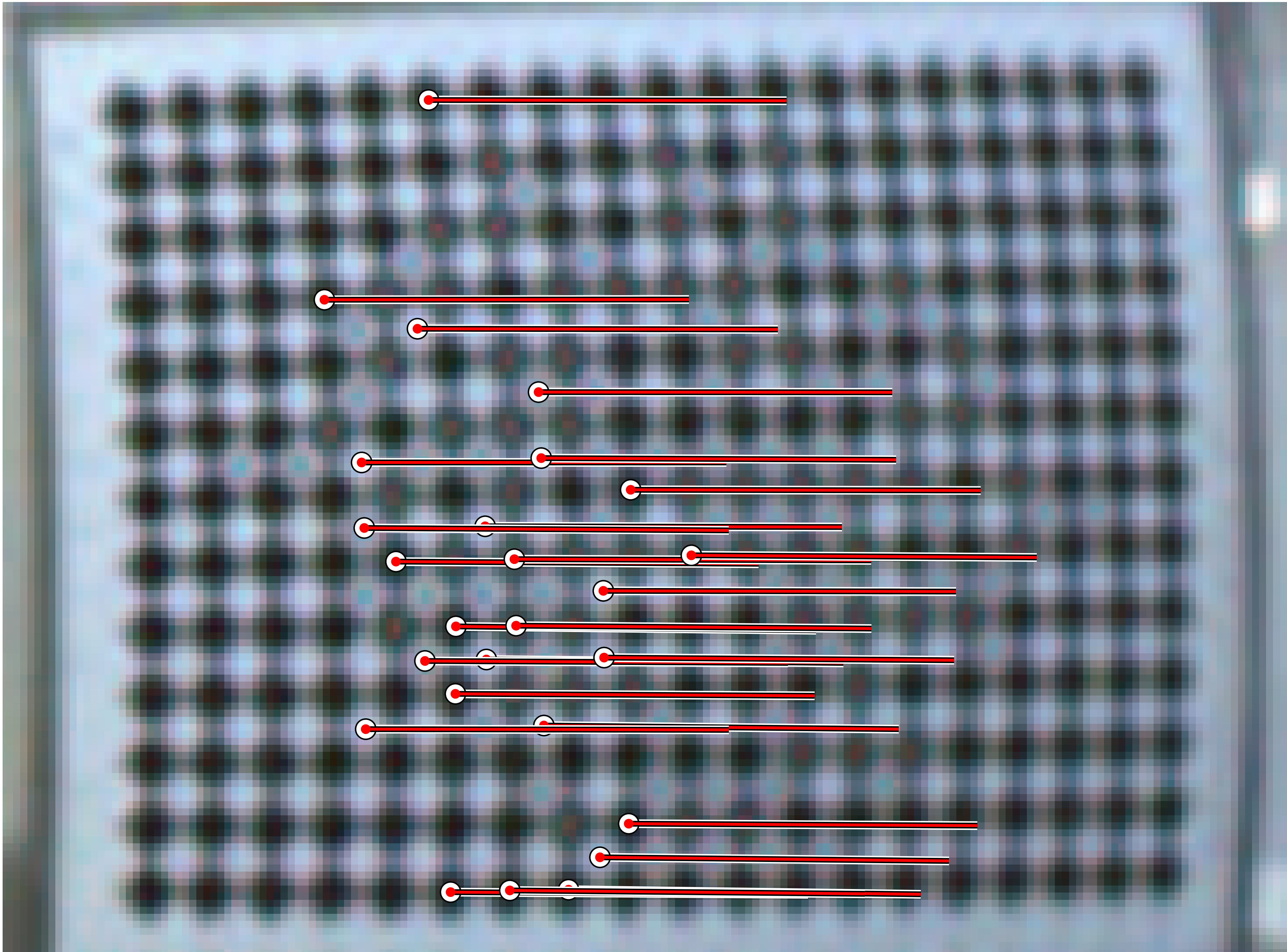
F
x
y
z
p
u
v
π
u

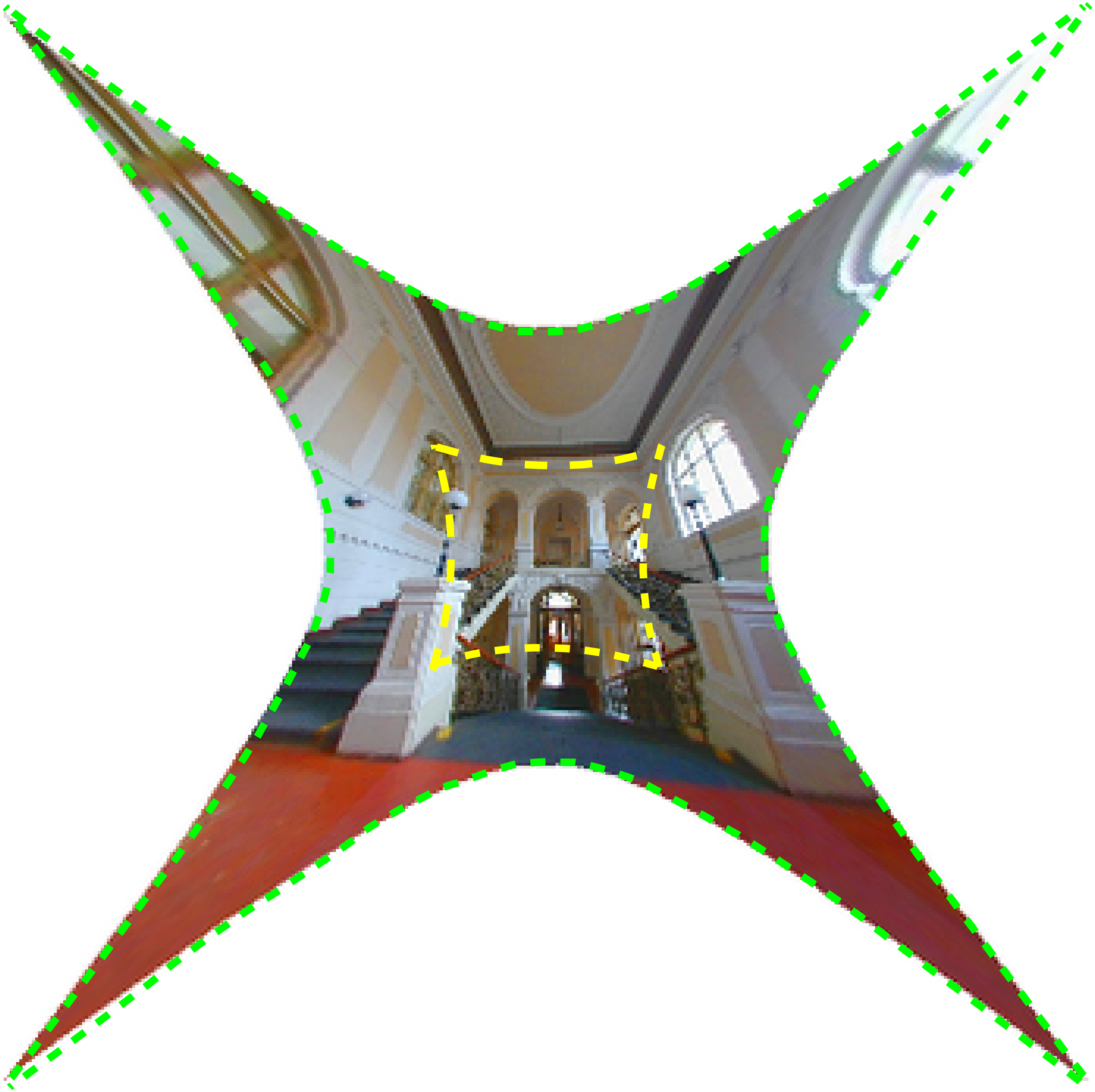


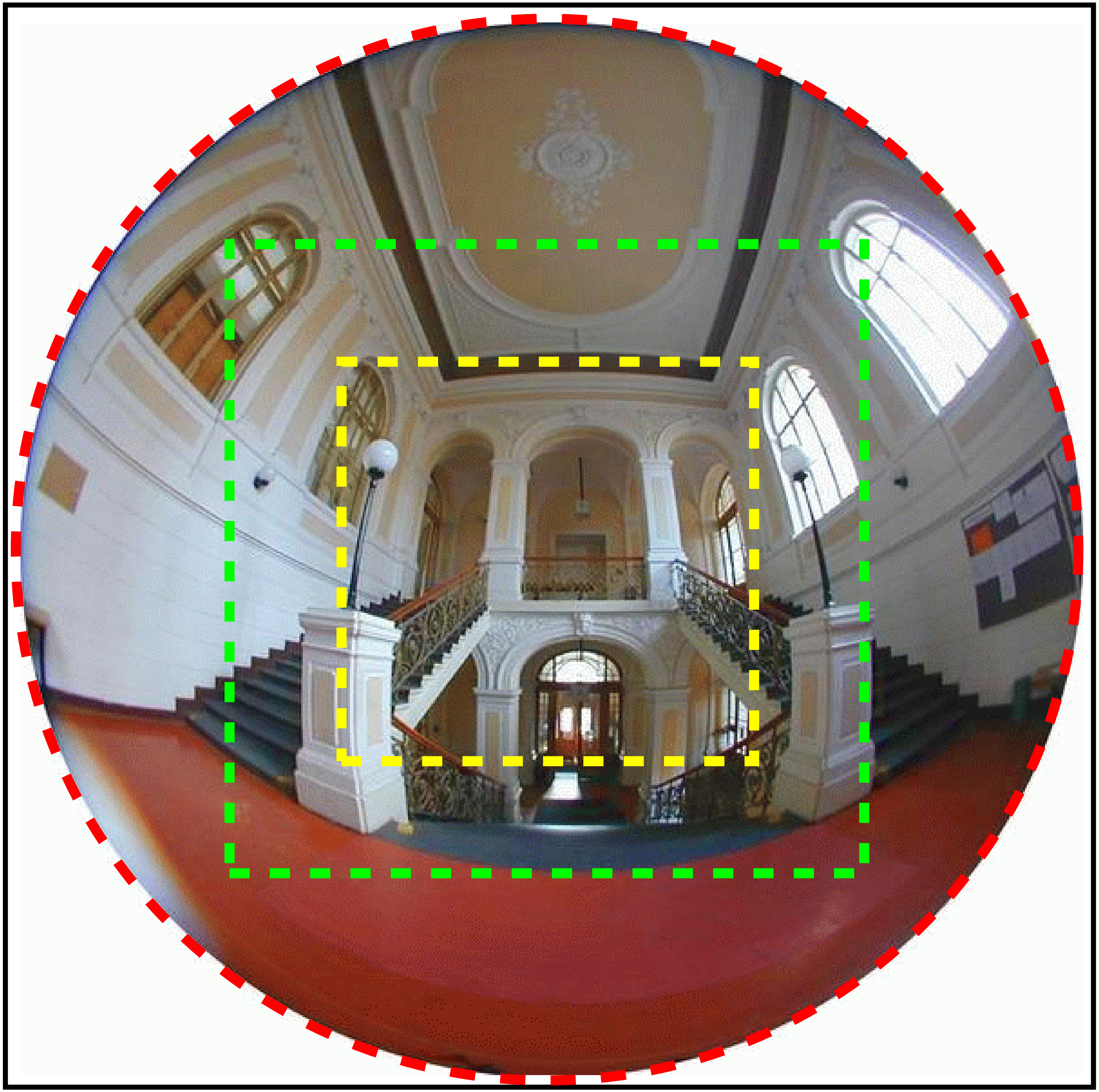
F_1
F_2
$\mathbf{p}_1$
$\mathbf{p}_2$
$\mathbf{X}$
π
$\mathbf{u}_1$
π
$\mathbf{u}_2$

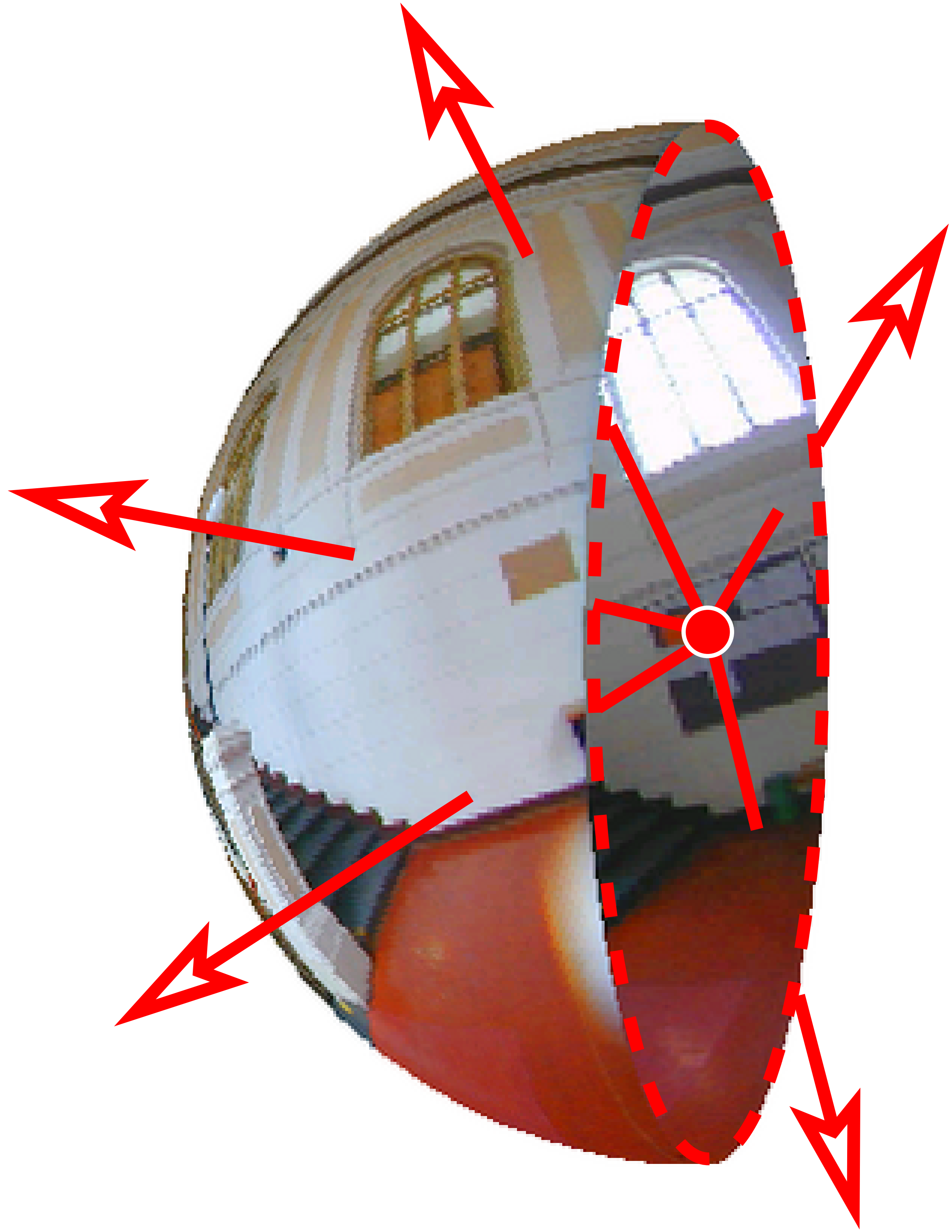




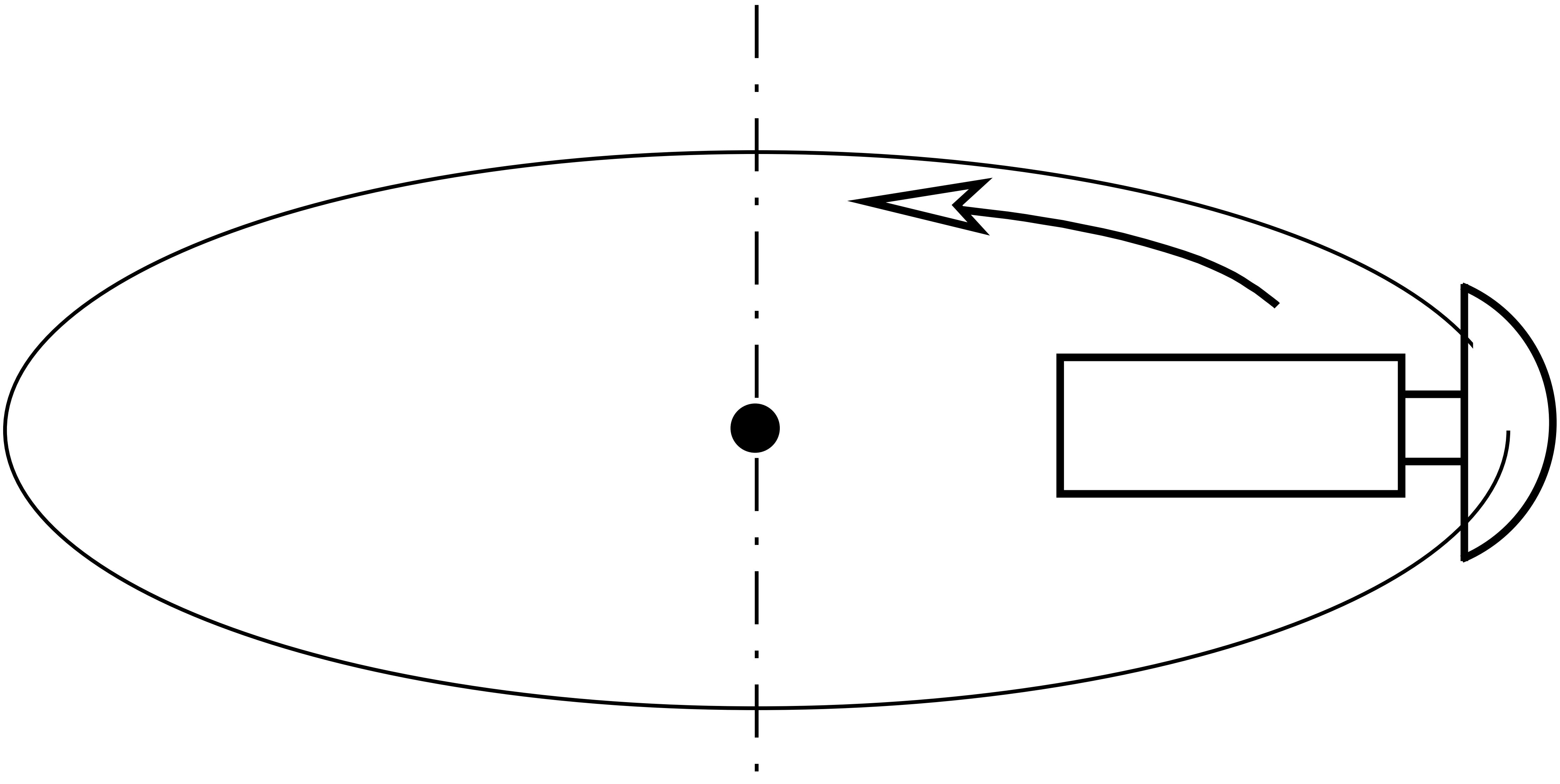


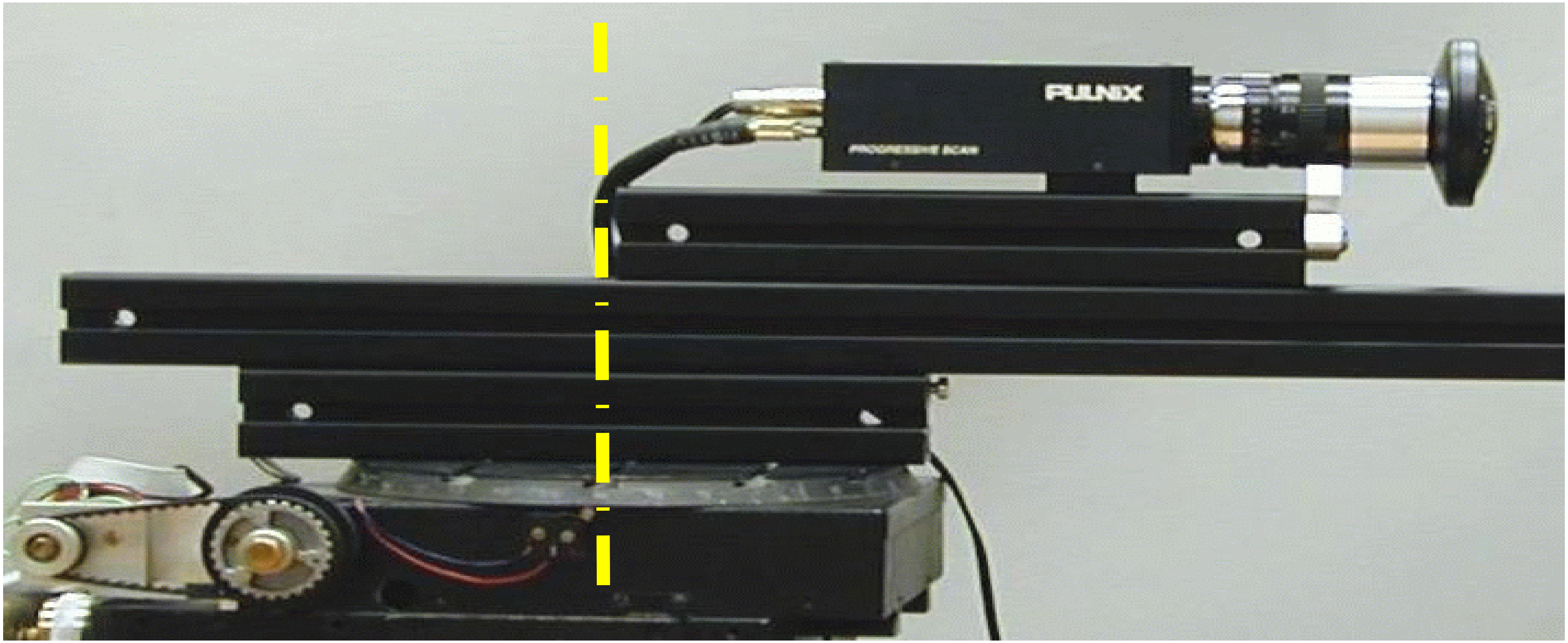


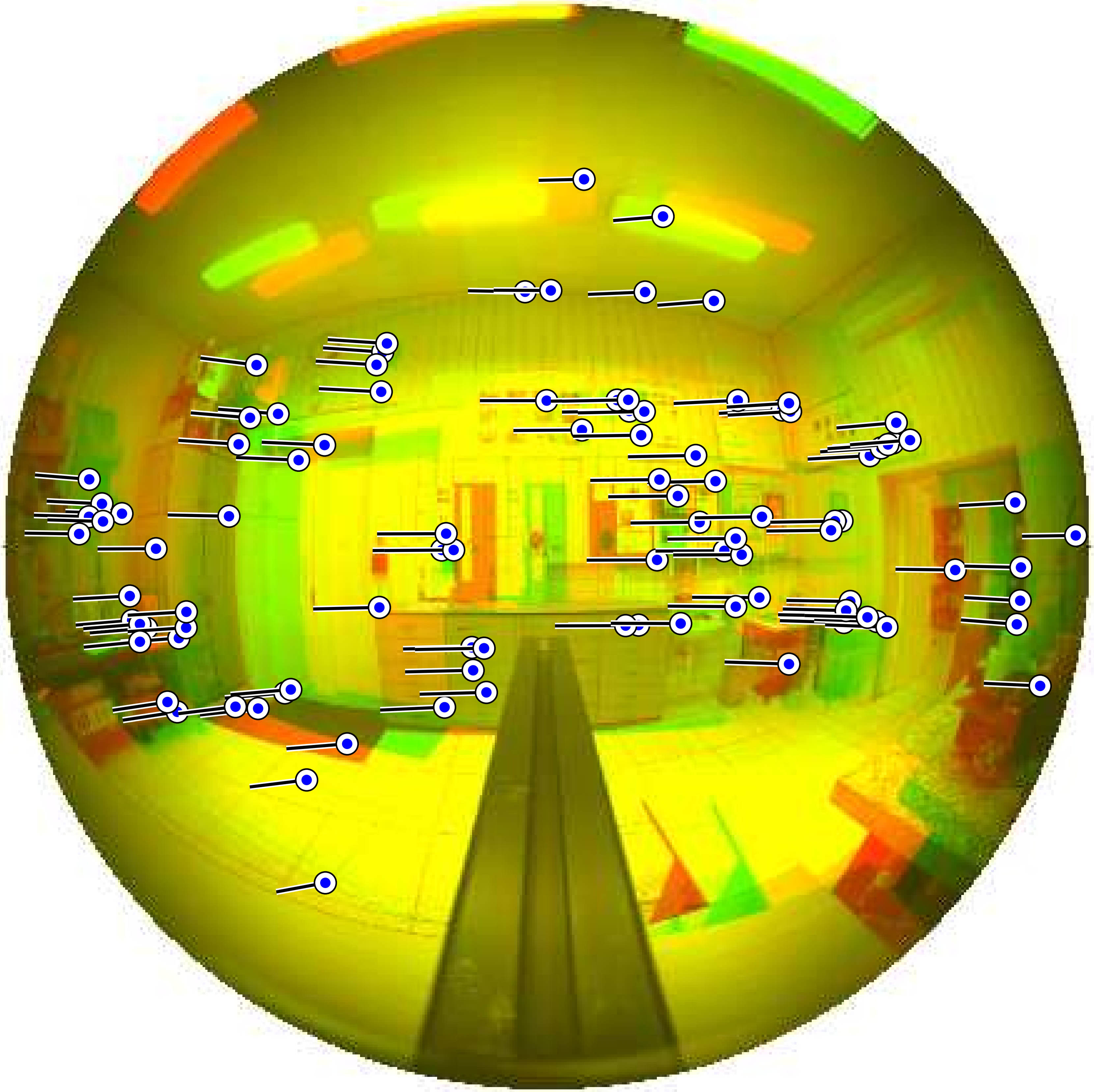


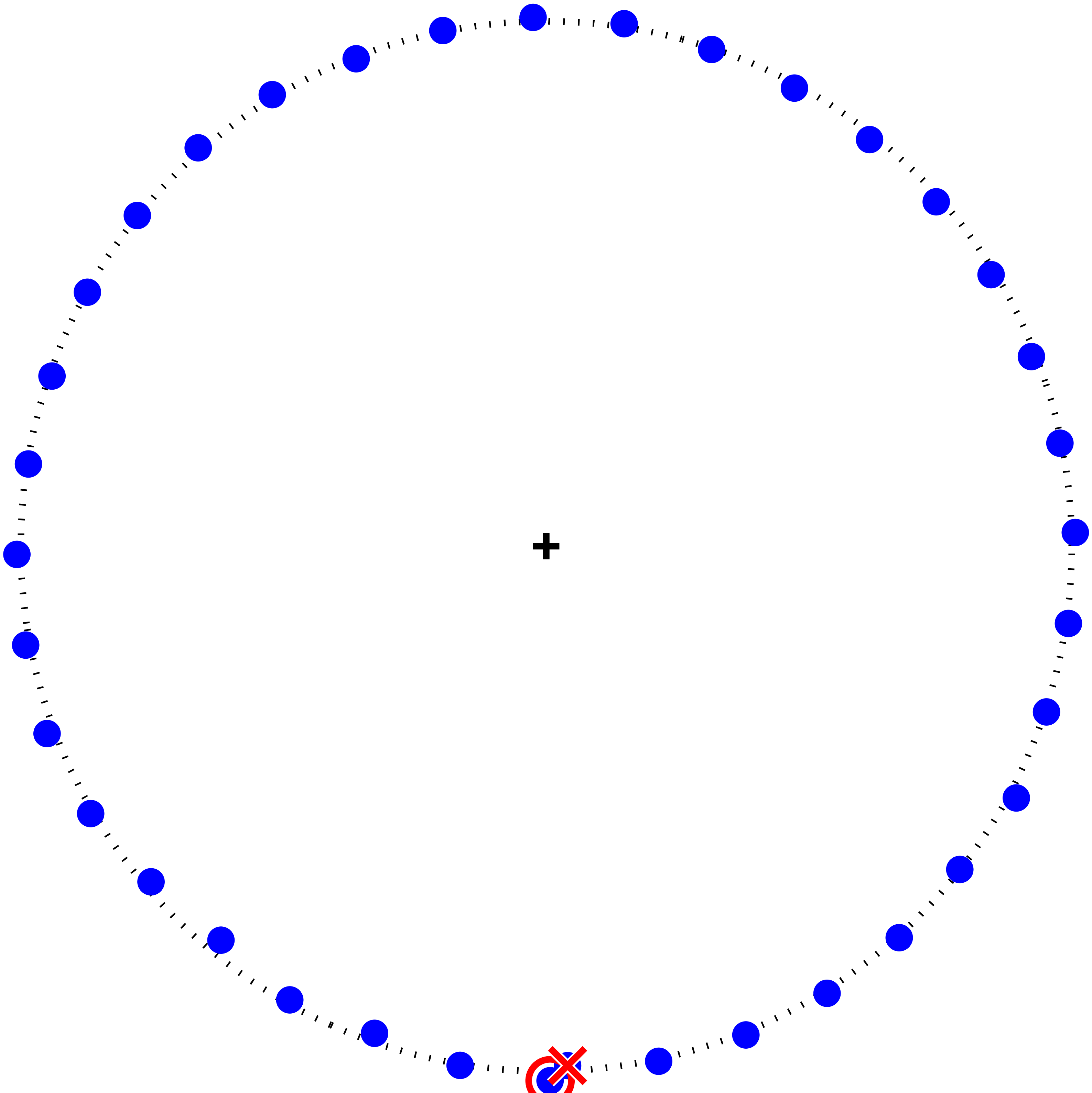



Nikon
DIGITAL CAMERA
COOLPIX
950




PULNIX
PROGRESSIVE SCAN






PULNiX
PROGRESSIVE SCAN
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Canon


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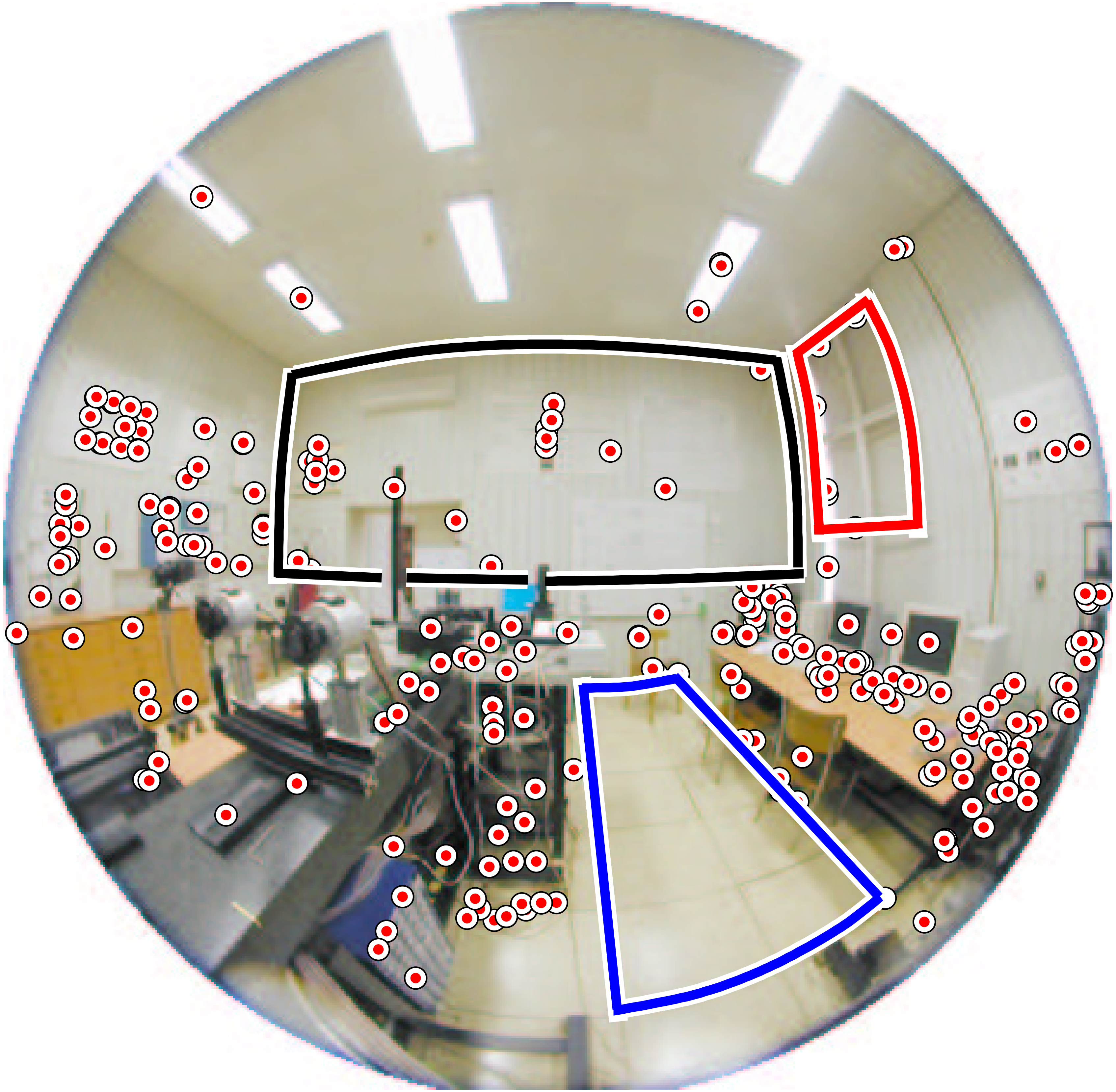
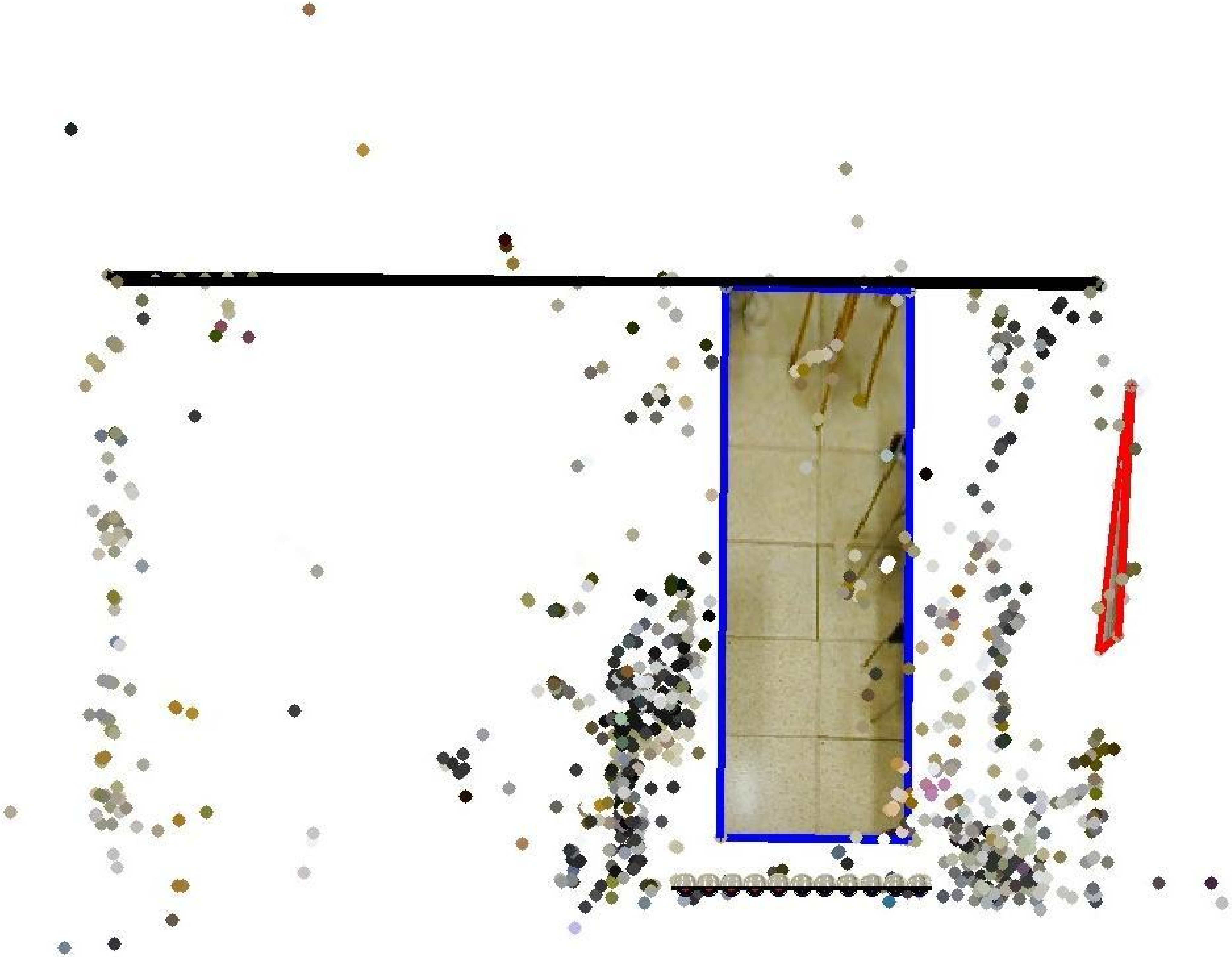
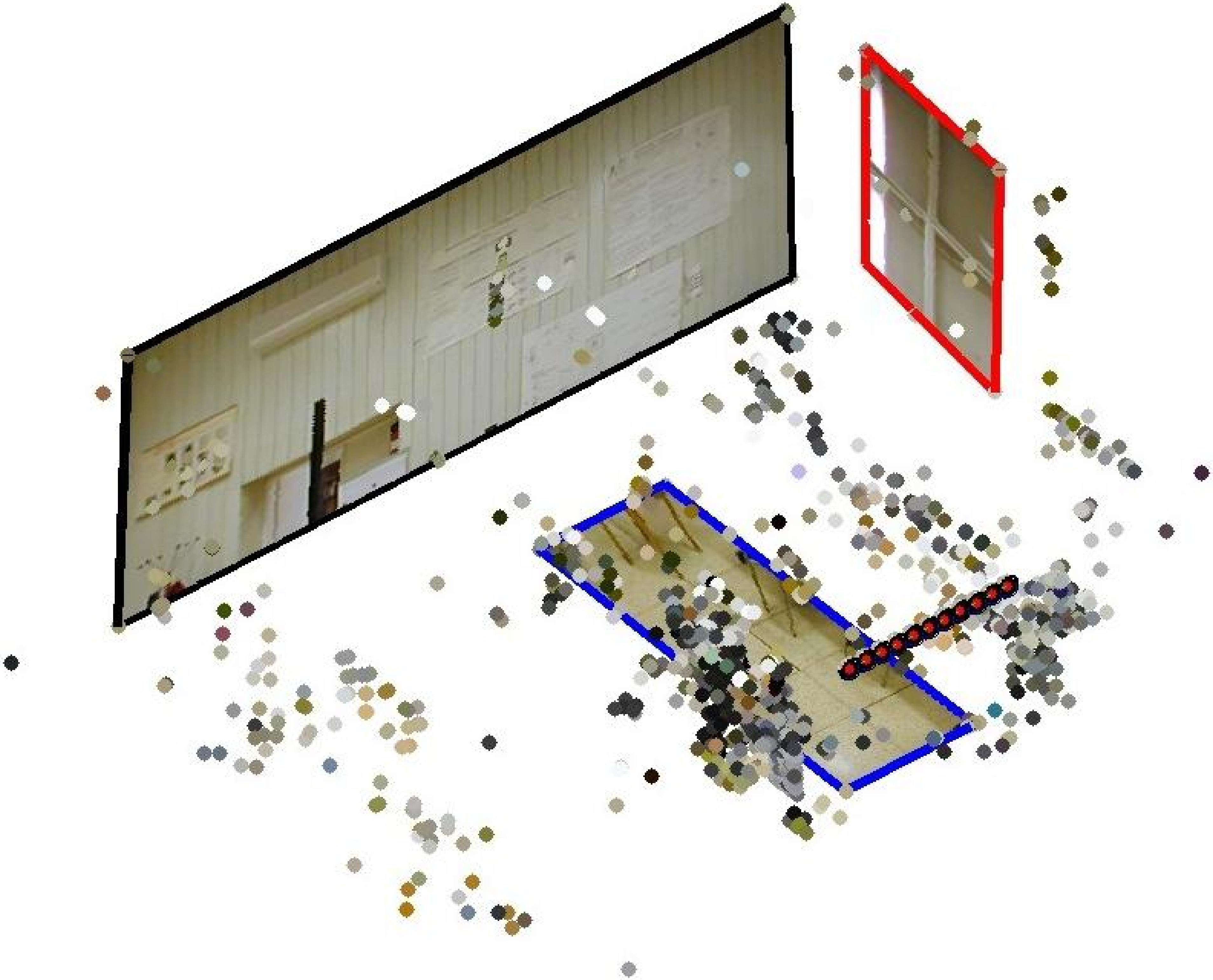
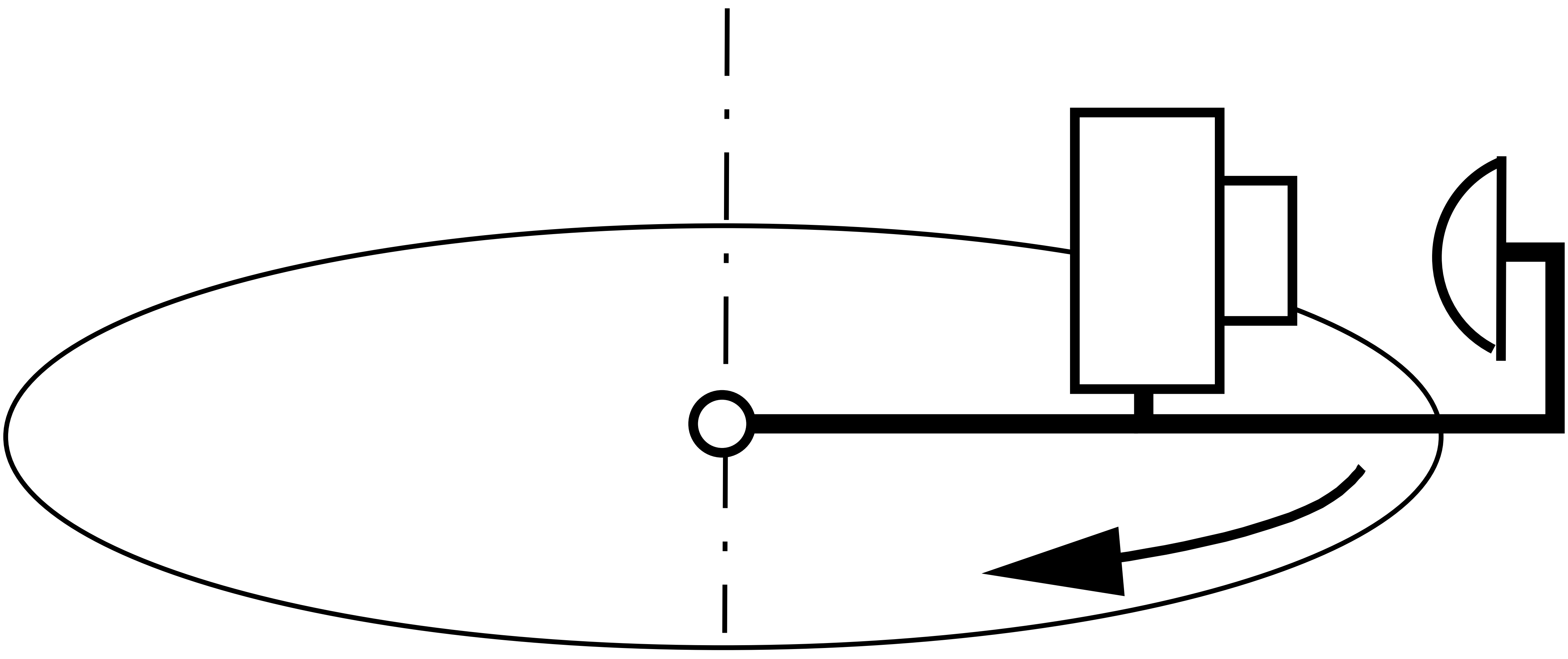
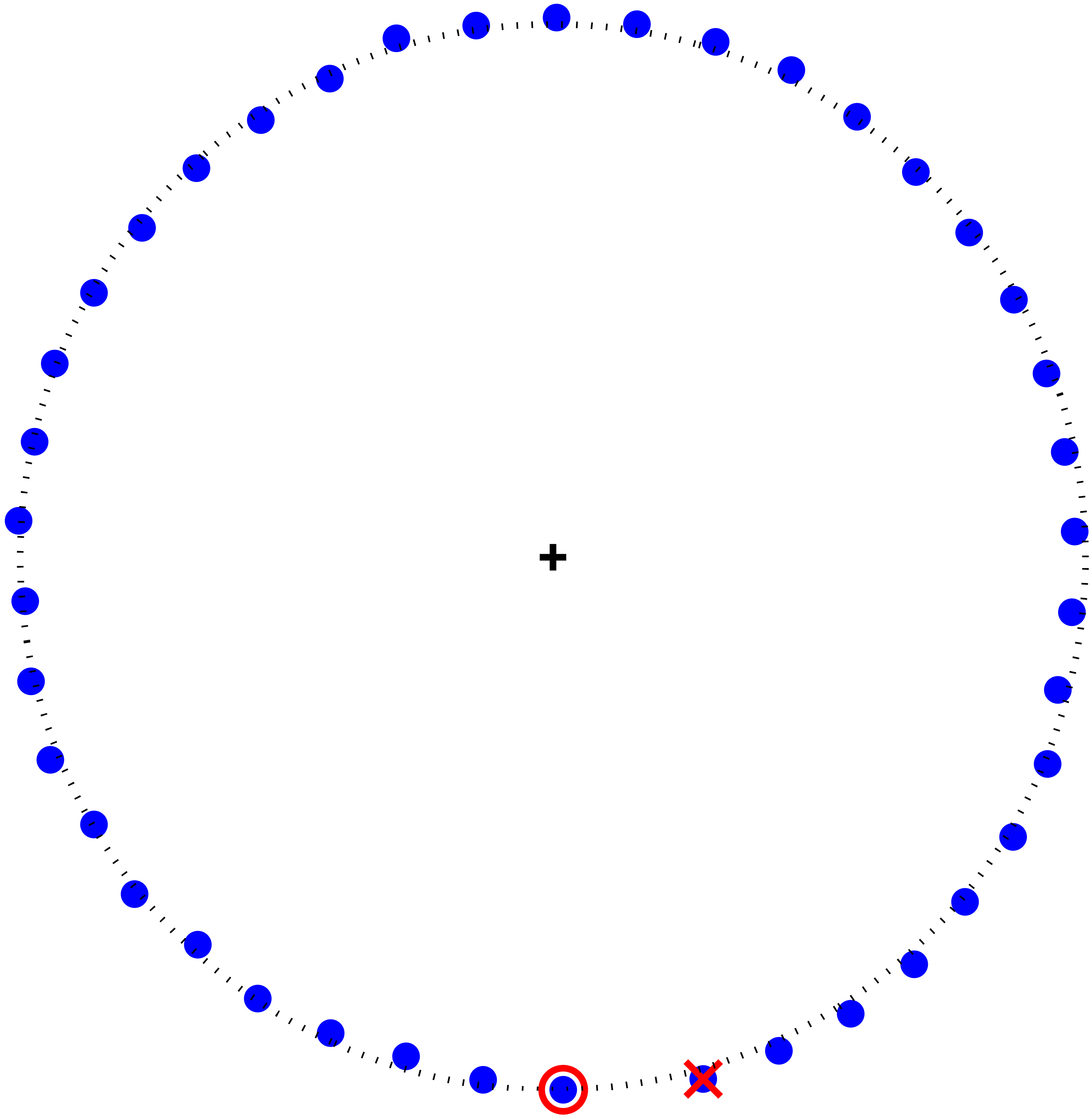


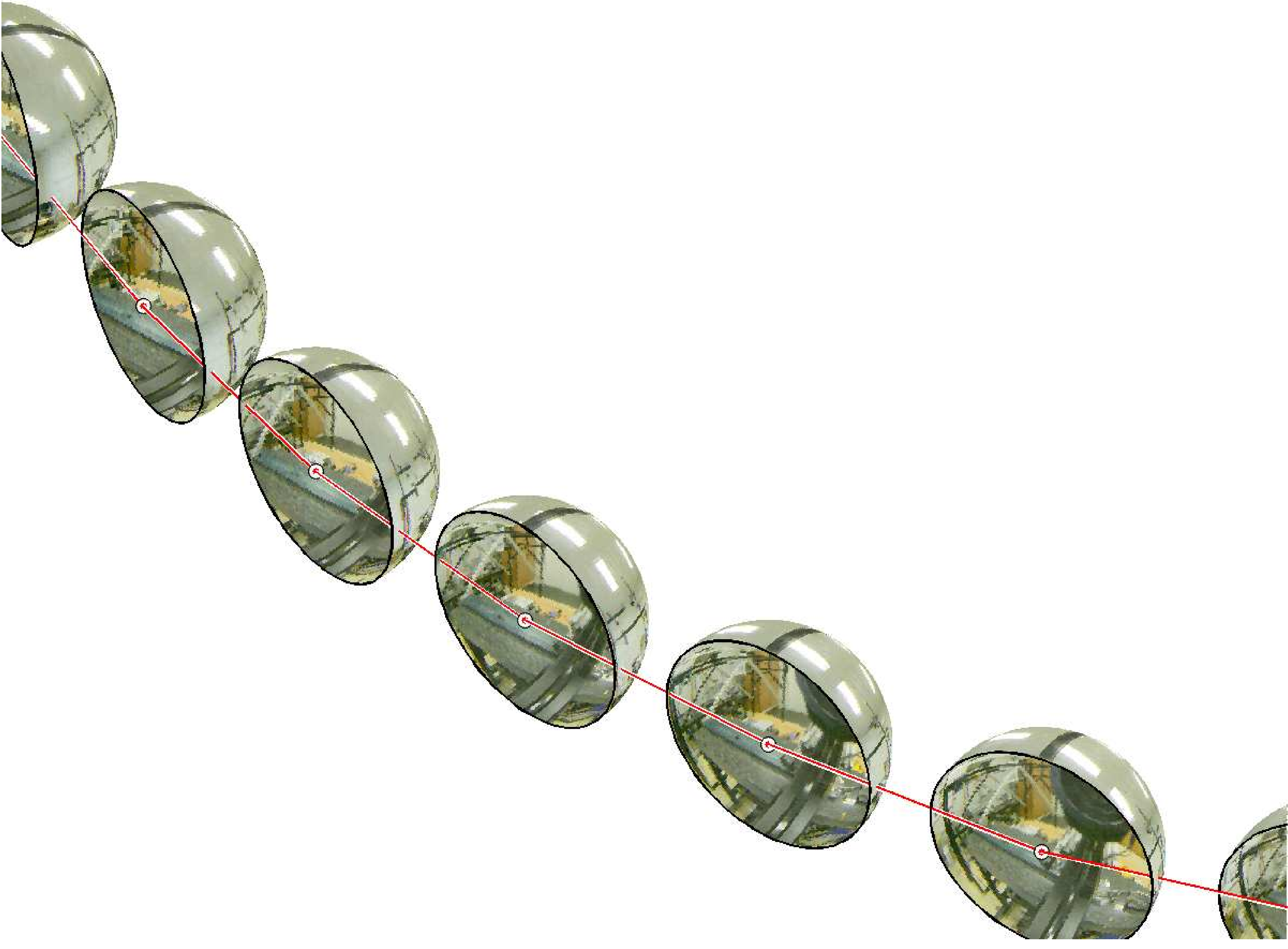


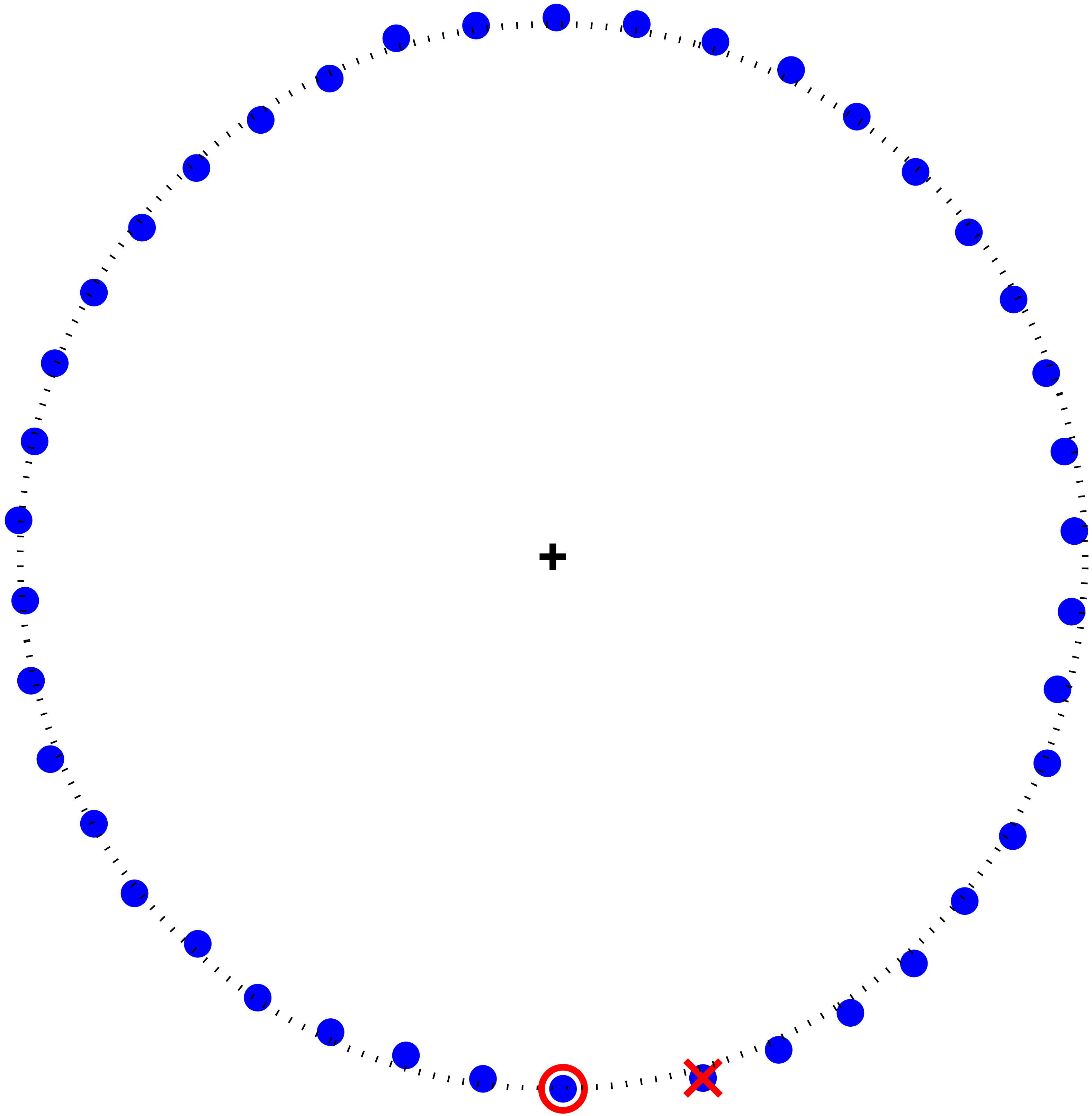


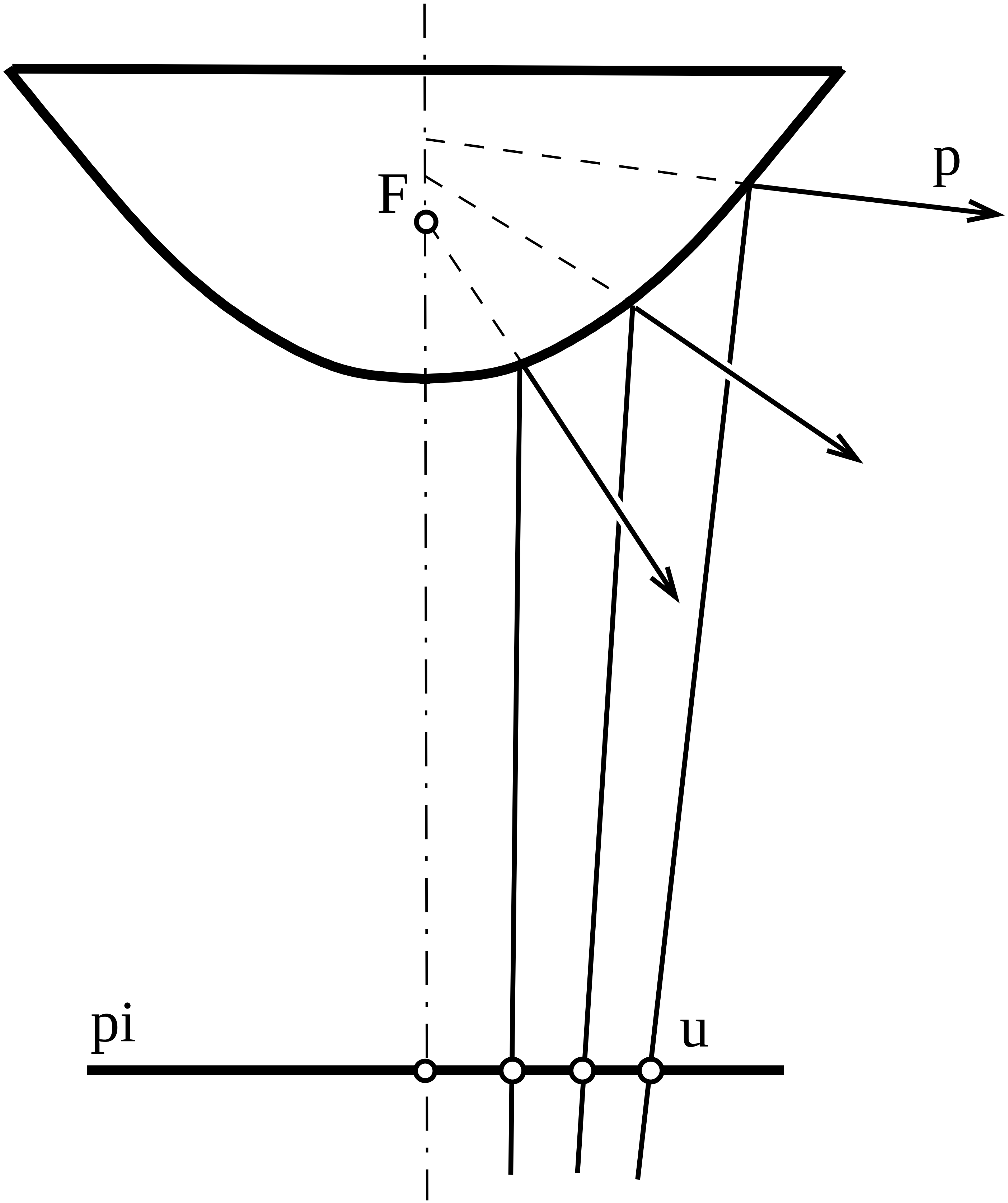

Nikon
DIGITAL CAMERA
COOLPIX
950










F
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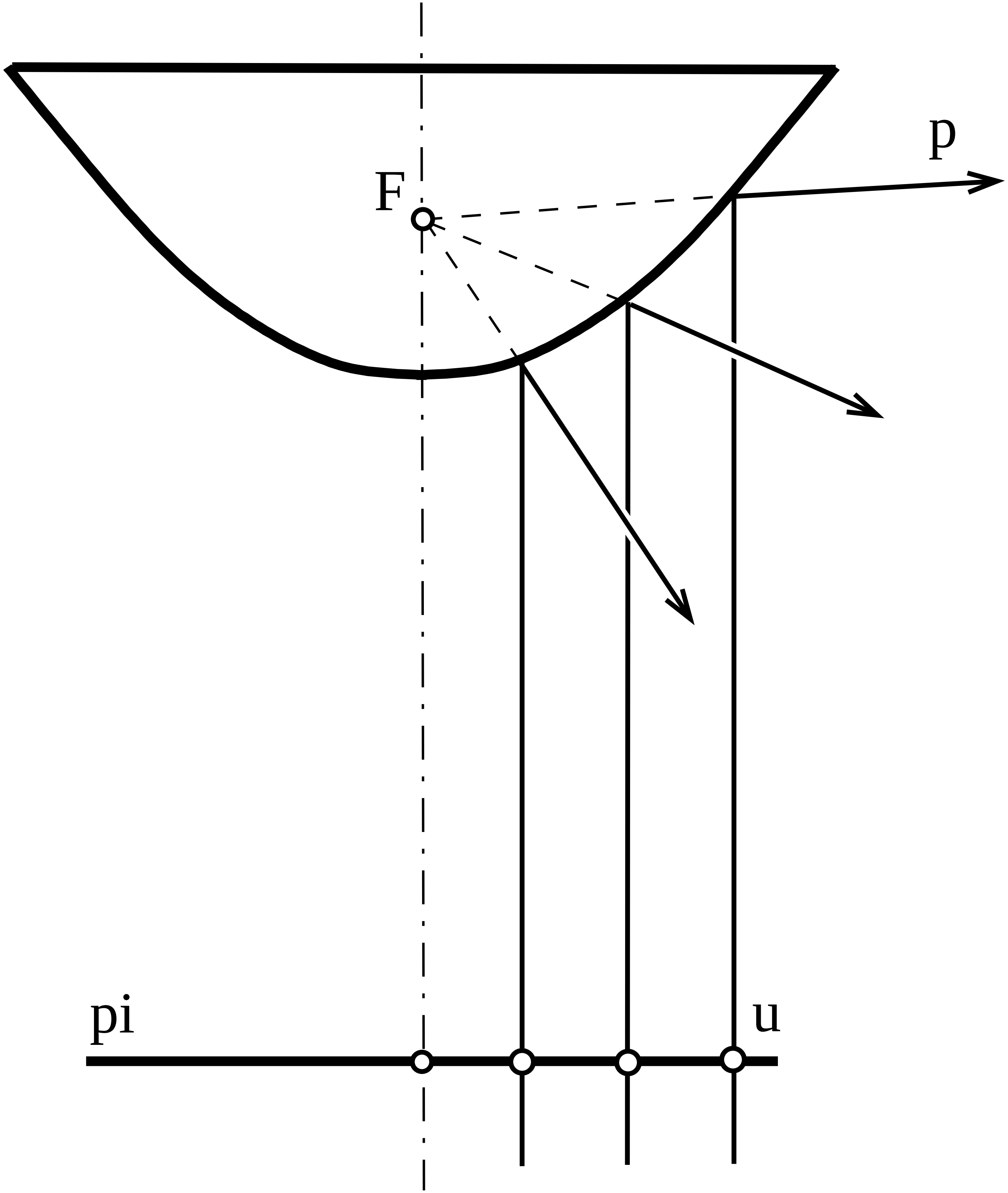
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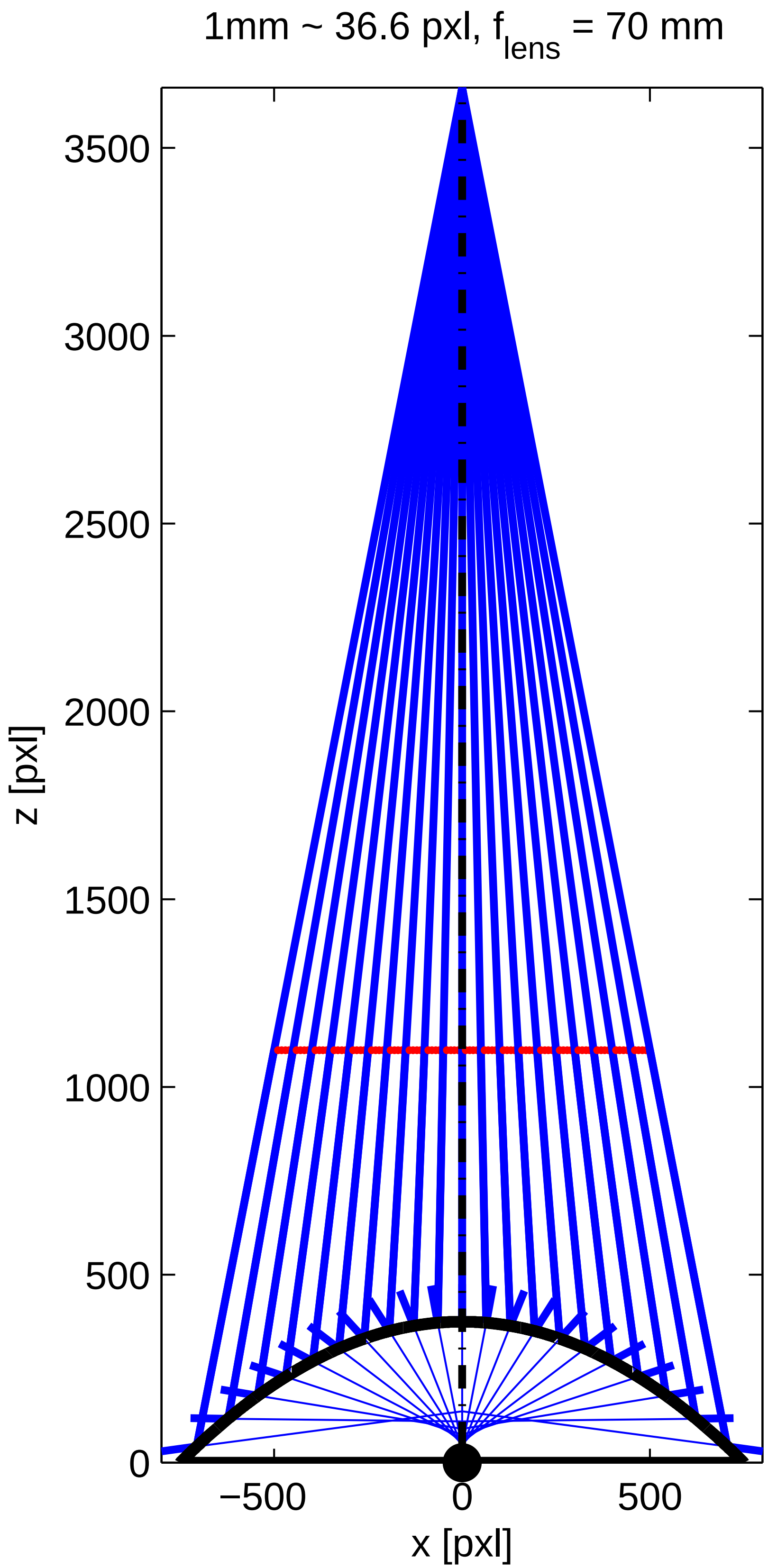
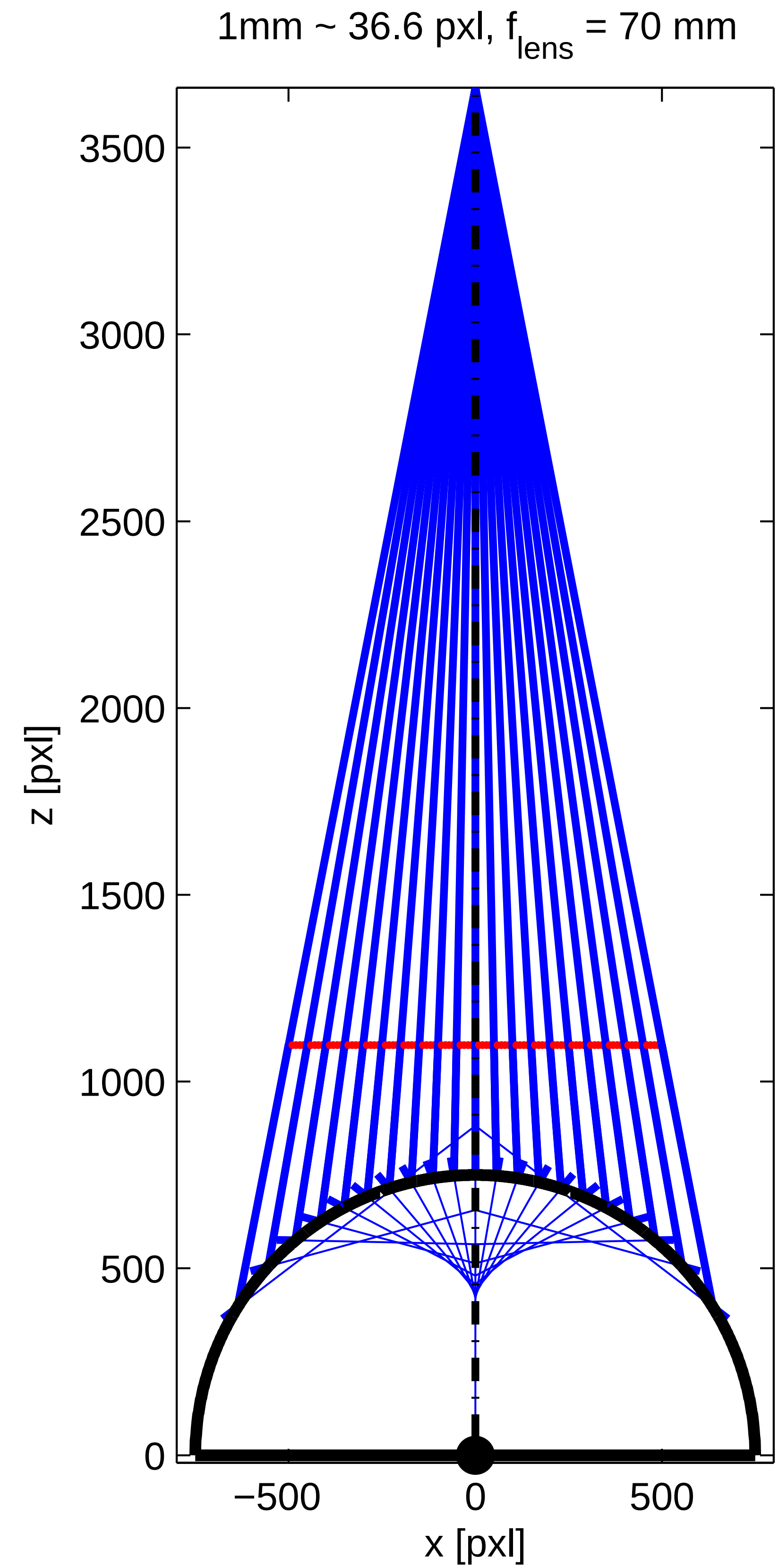


1mm ~ 36.6 pxl, f lens = 70 mm
z [pxl]
x [pxl]
3500
3000
2500
2000
1500
1000
500
0
−500
0
500



1mm ~ 36.6 pxl, f_lens = 70 mm
z [pxl]
3500
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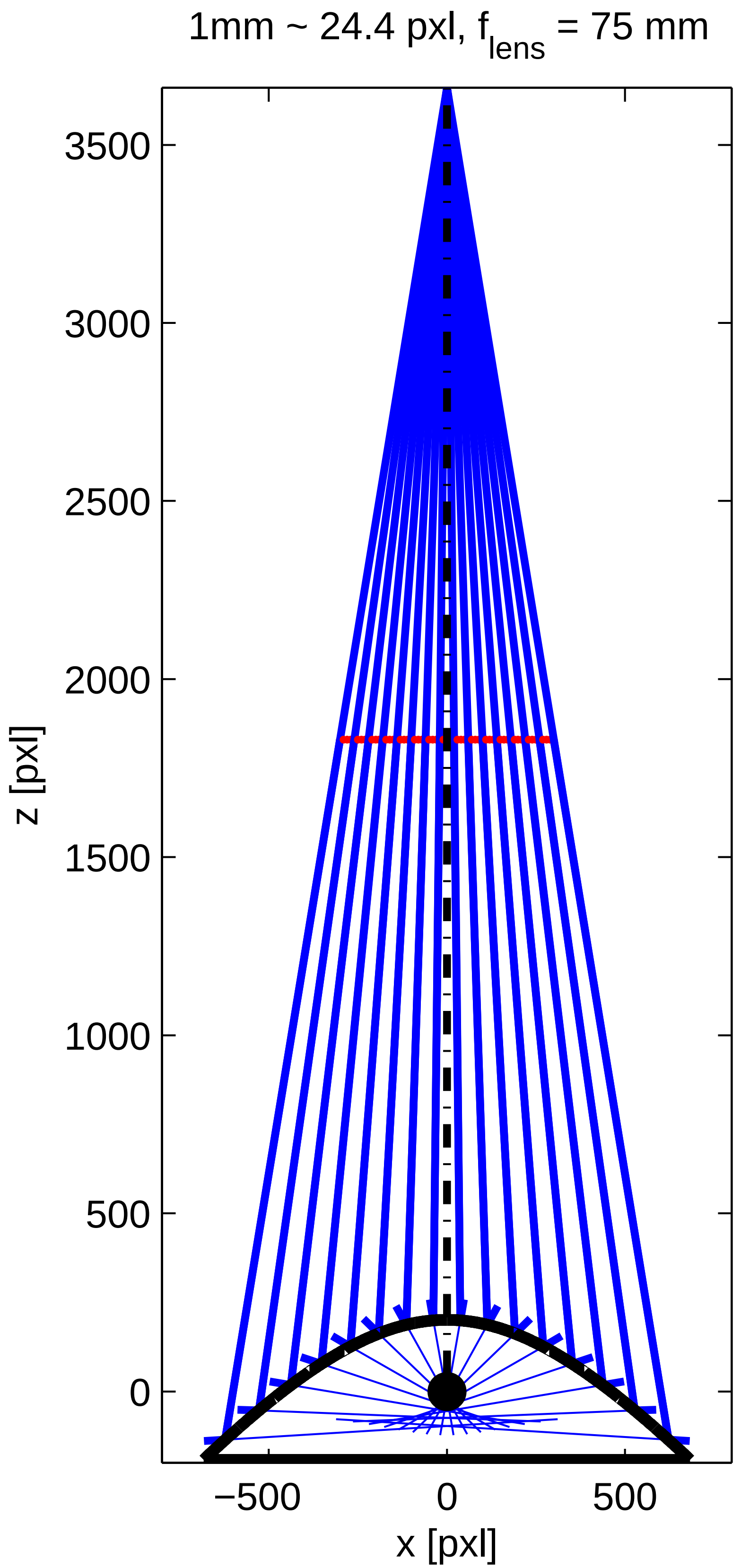

1mm ~ 24.4 pxl, f_lens = 75 mm
3500
3000
2500
2000
1500
1000
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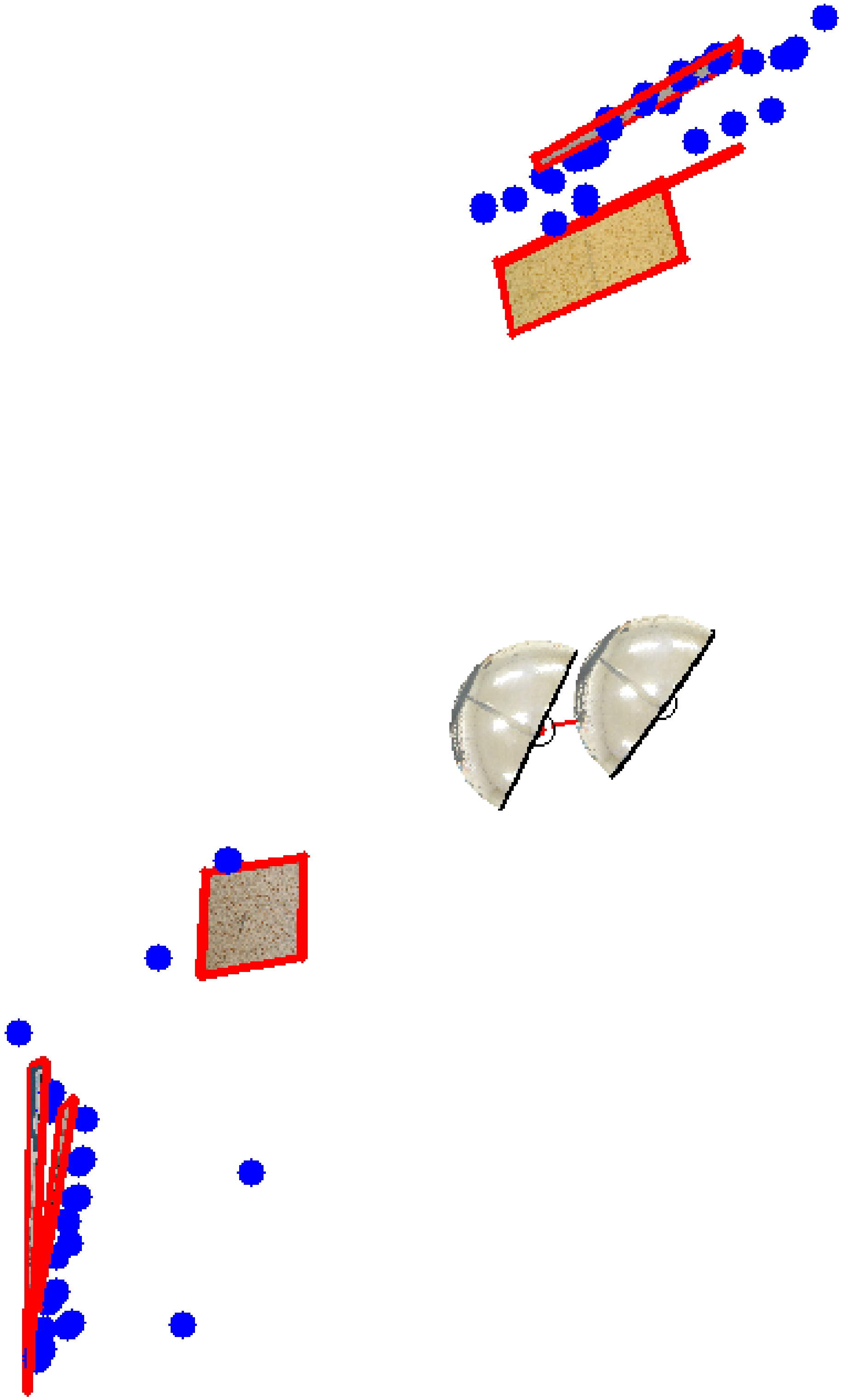
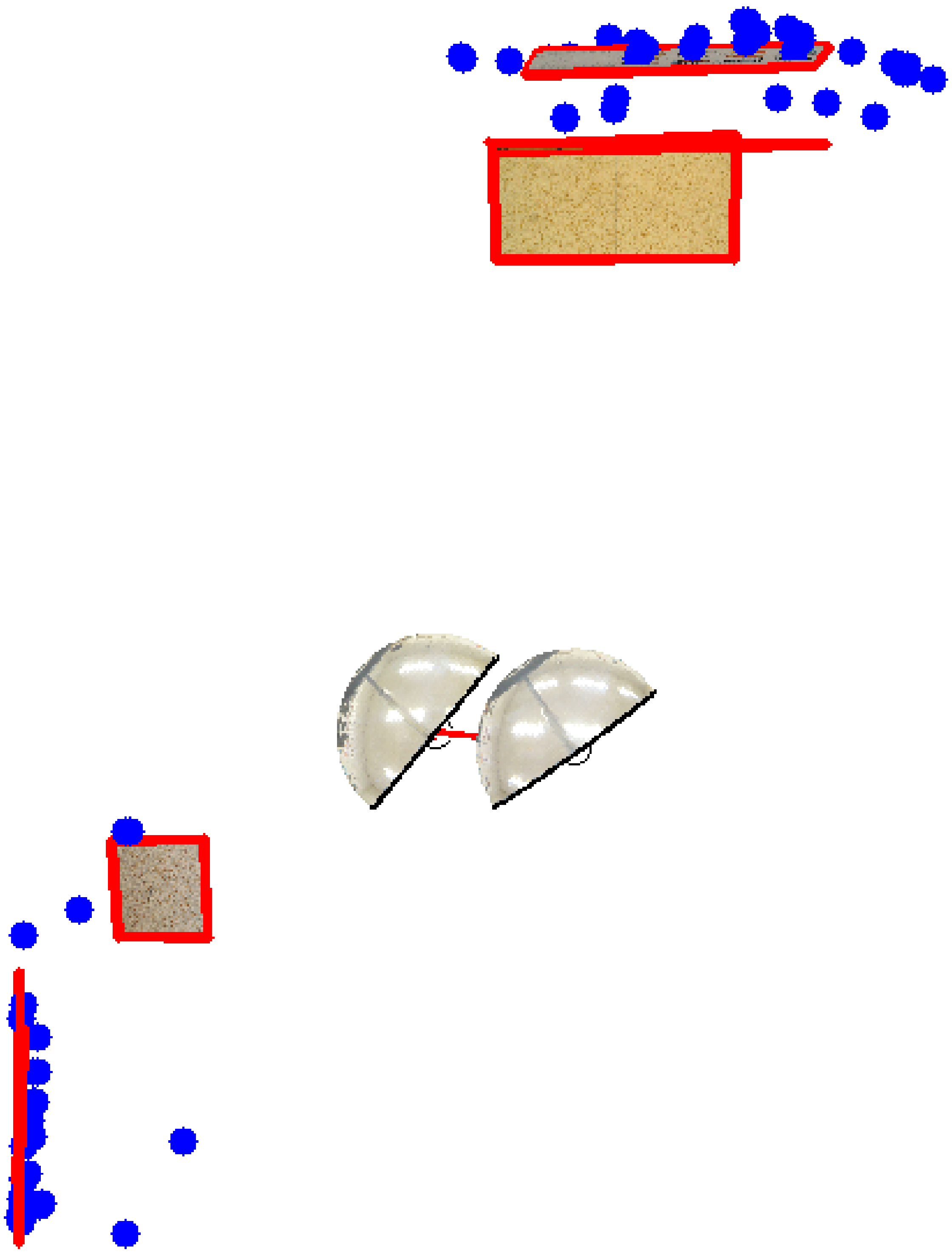
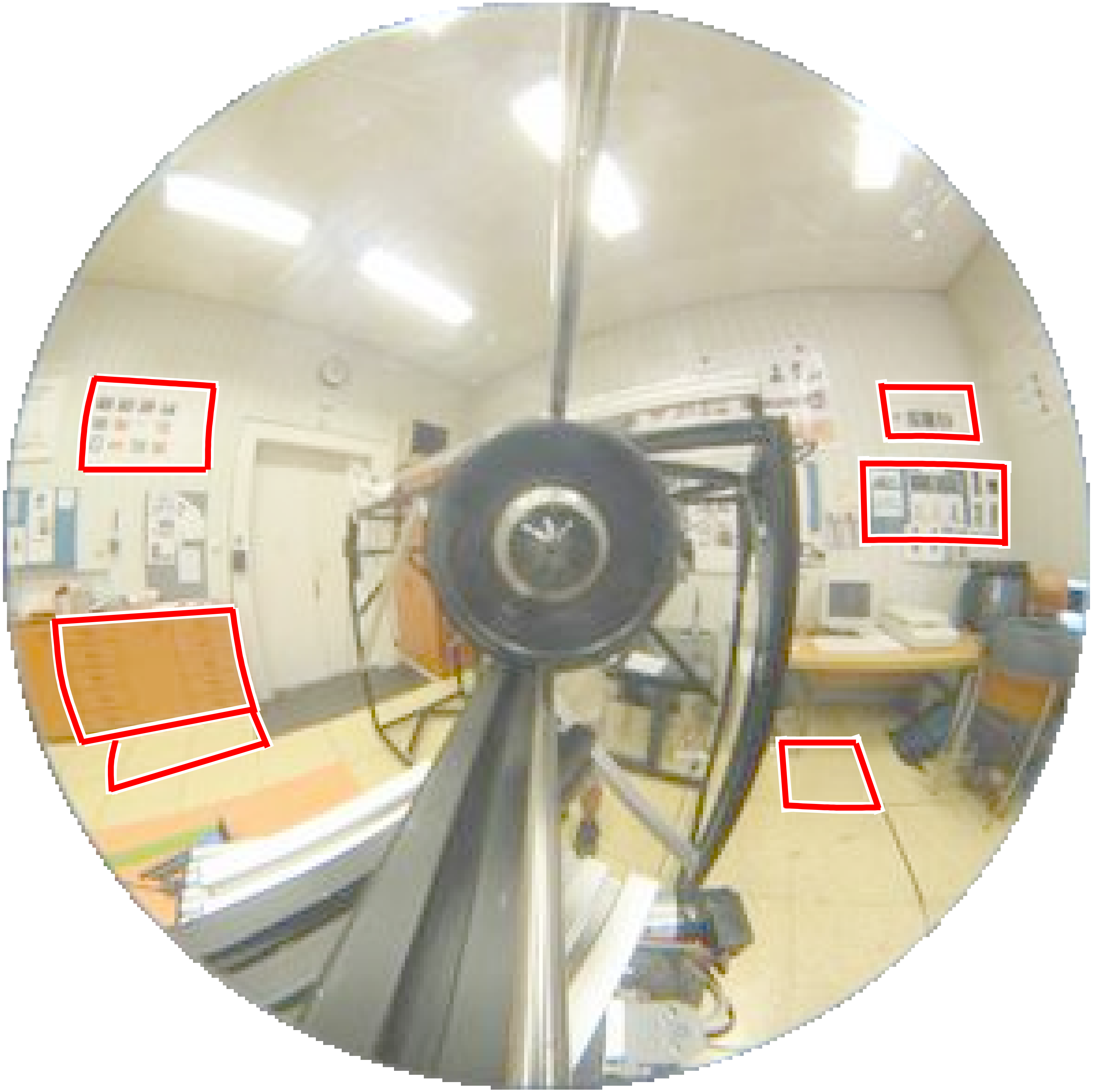
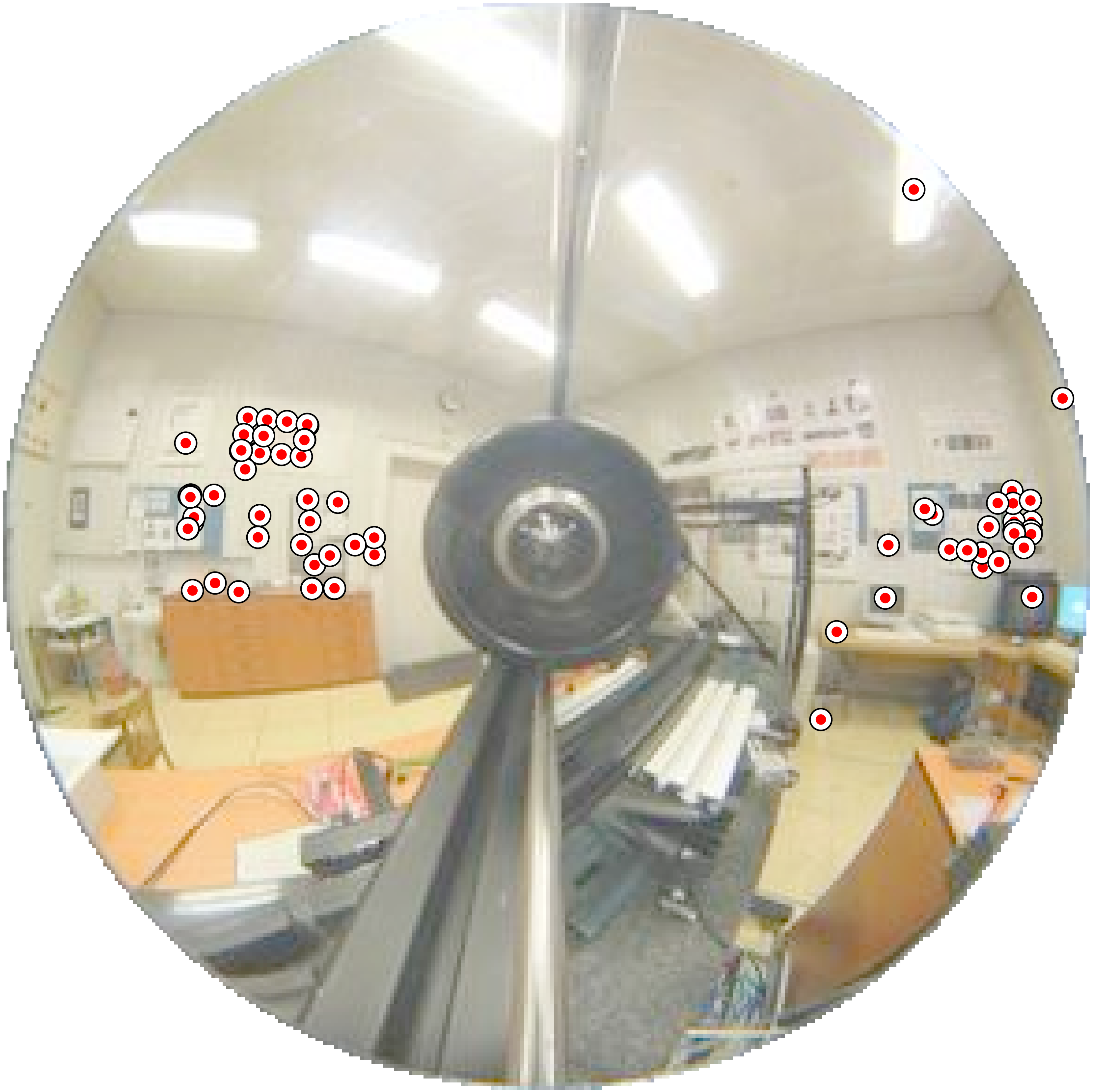
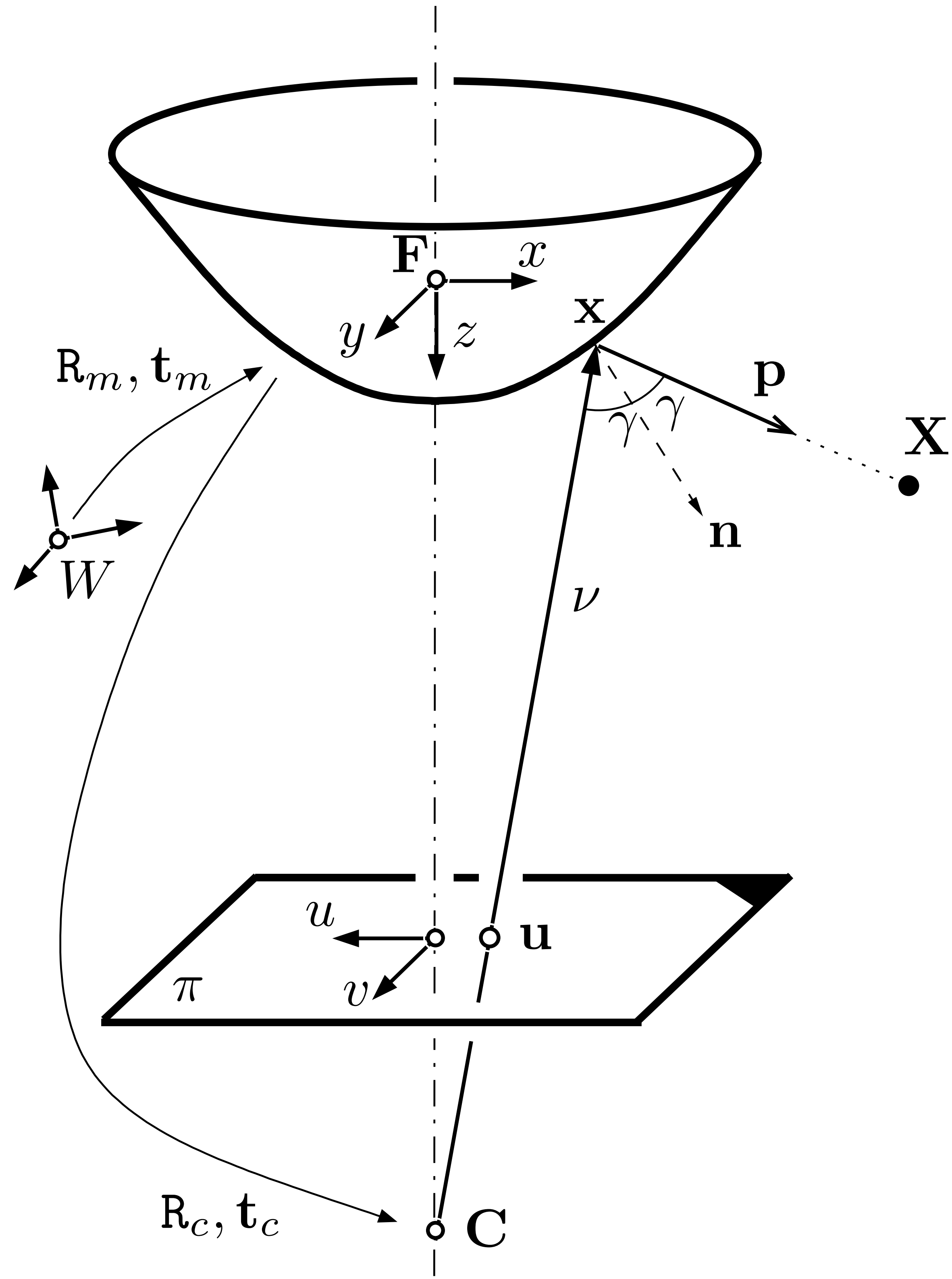
−500
0
500
x [pxl]











F
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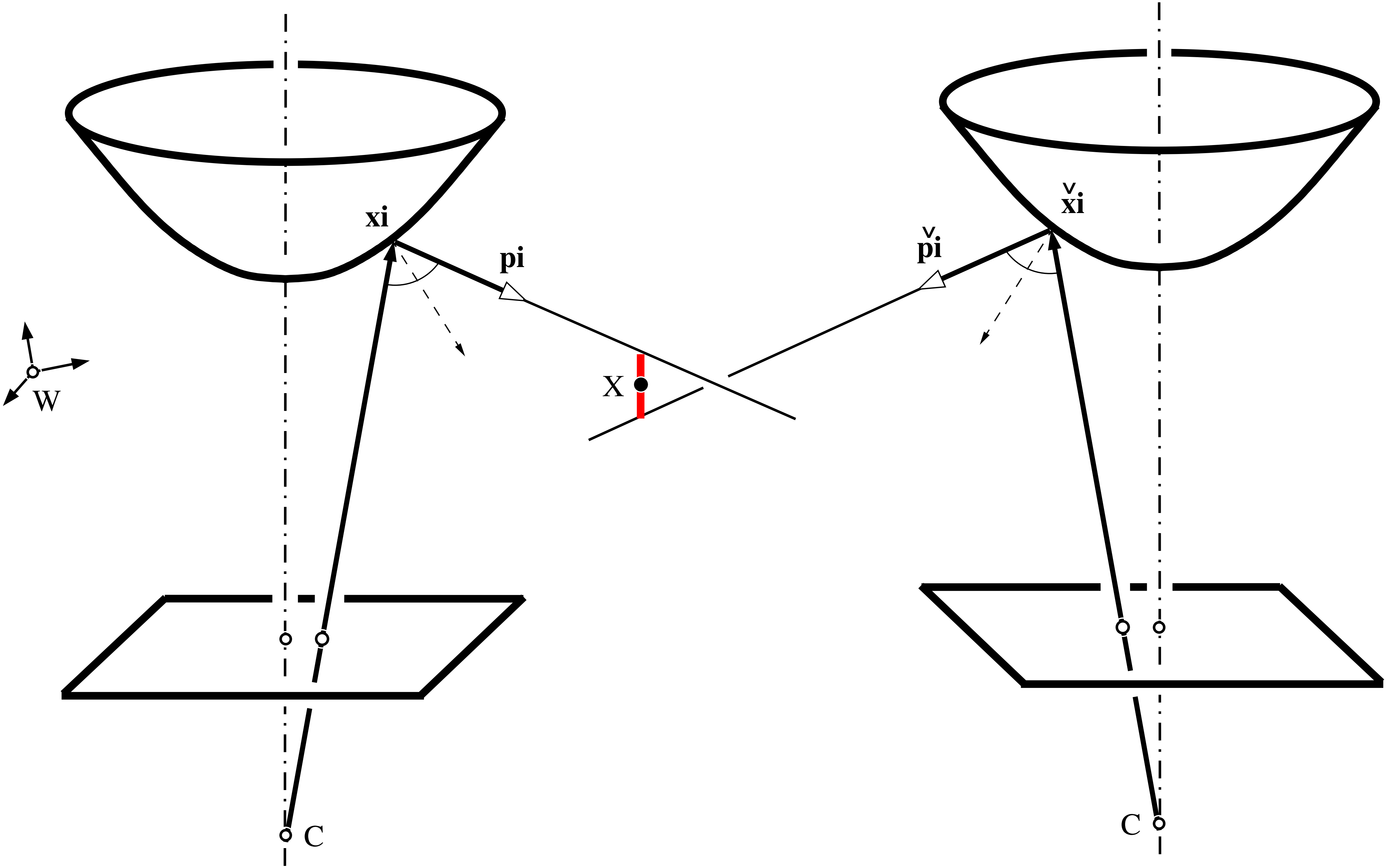

xi
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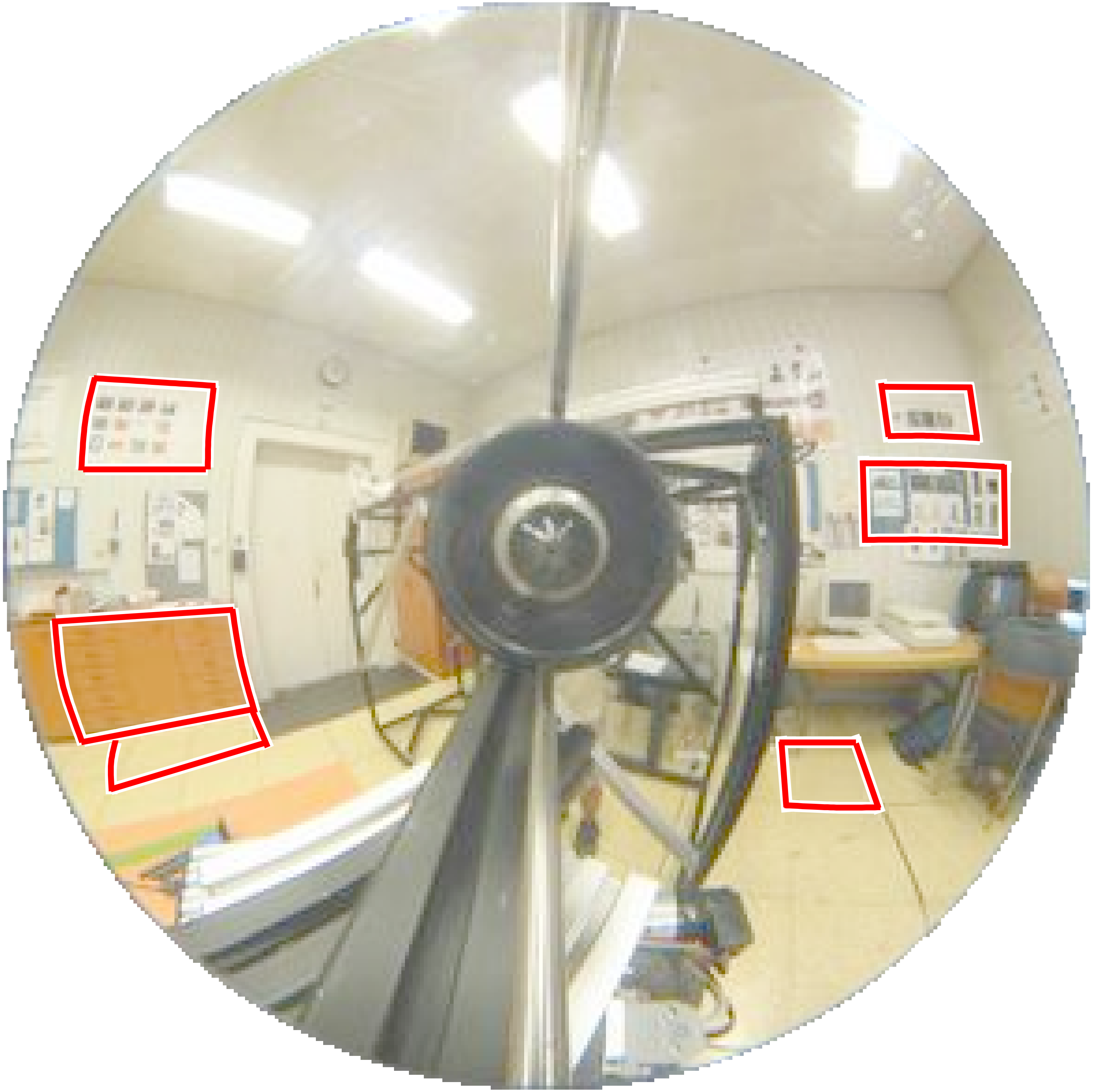

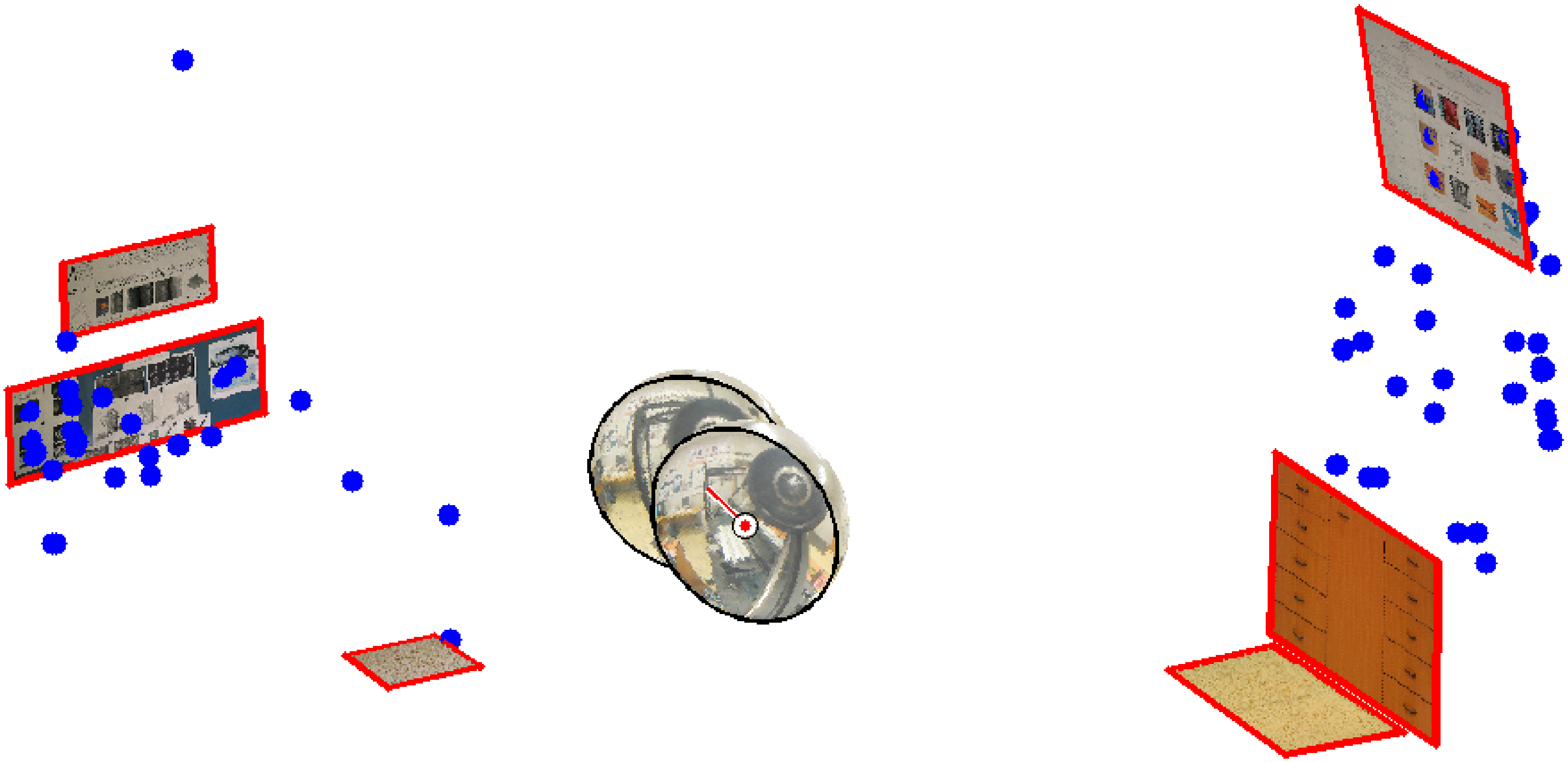

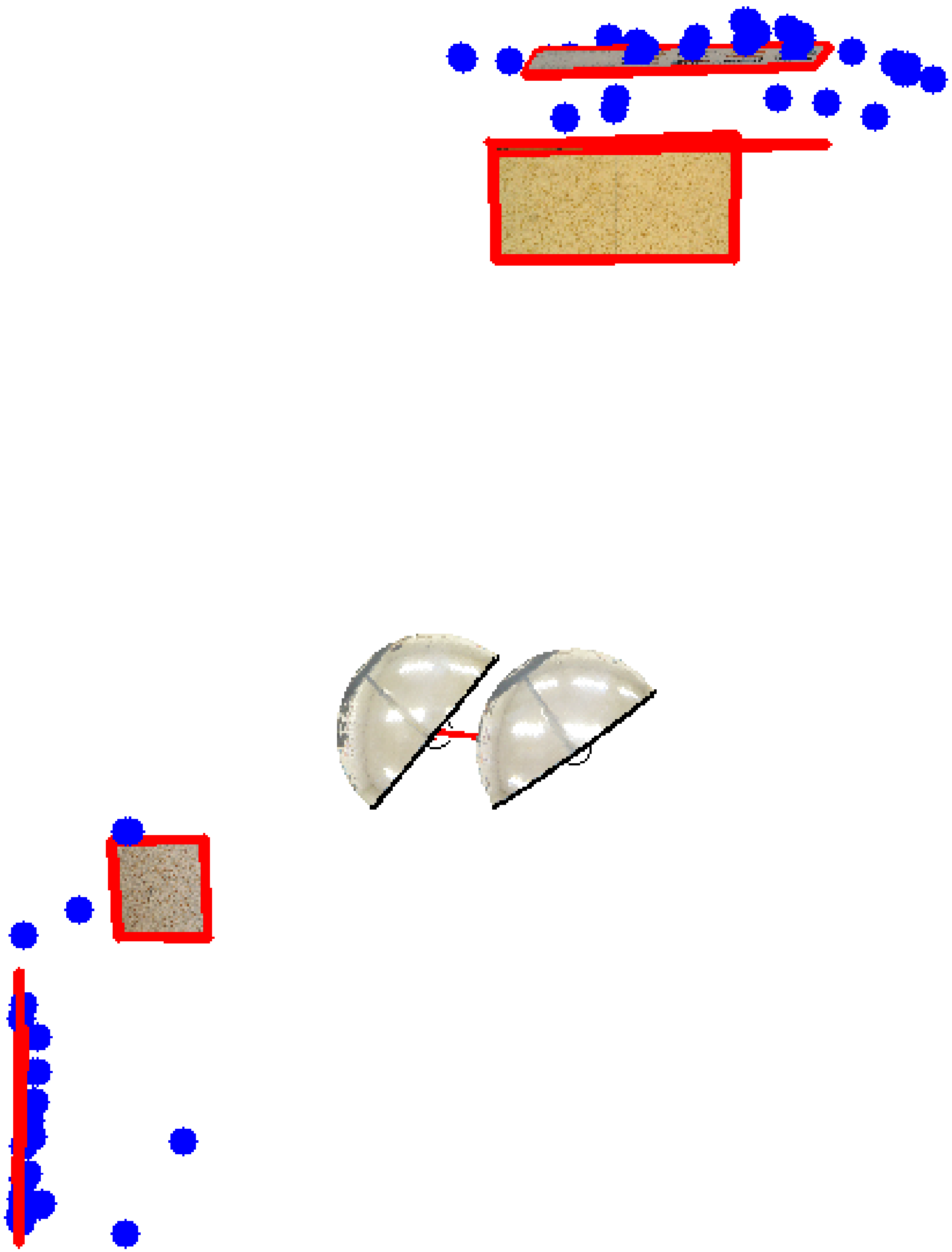

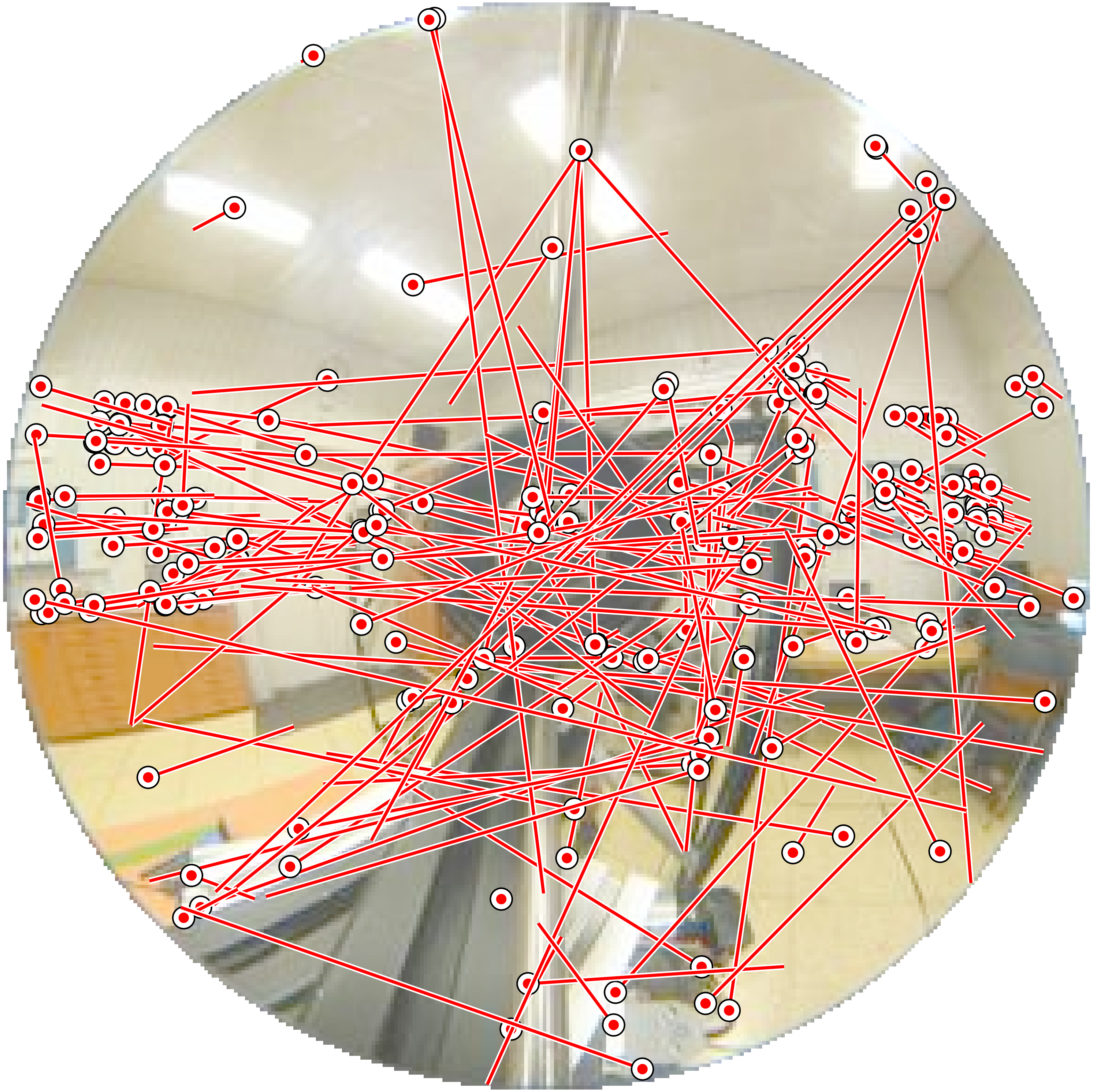

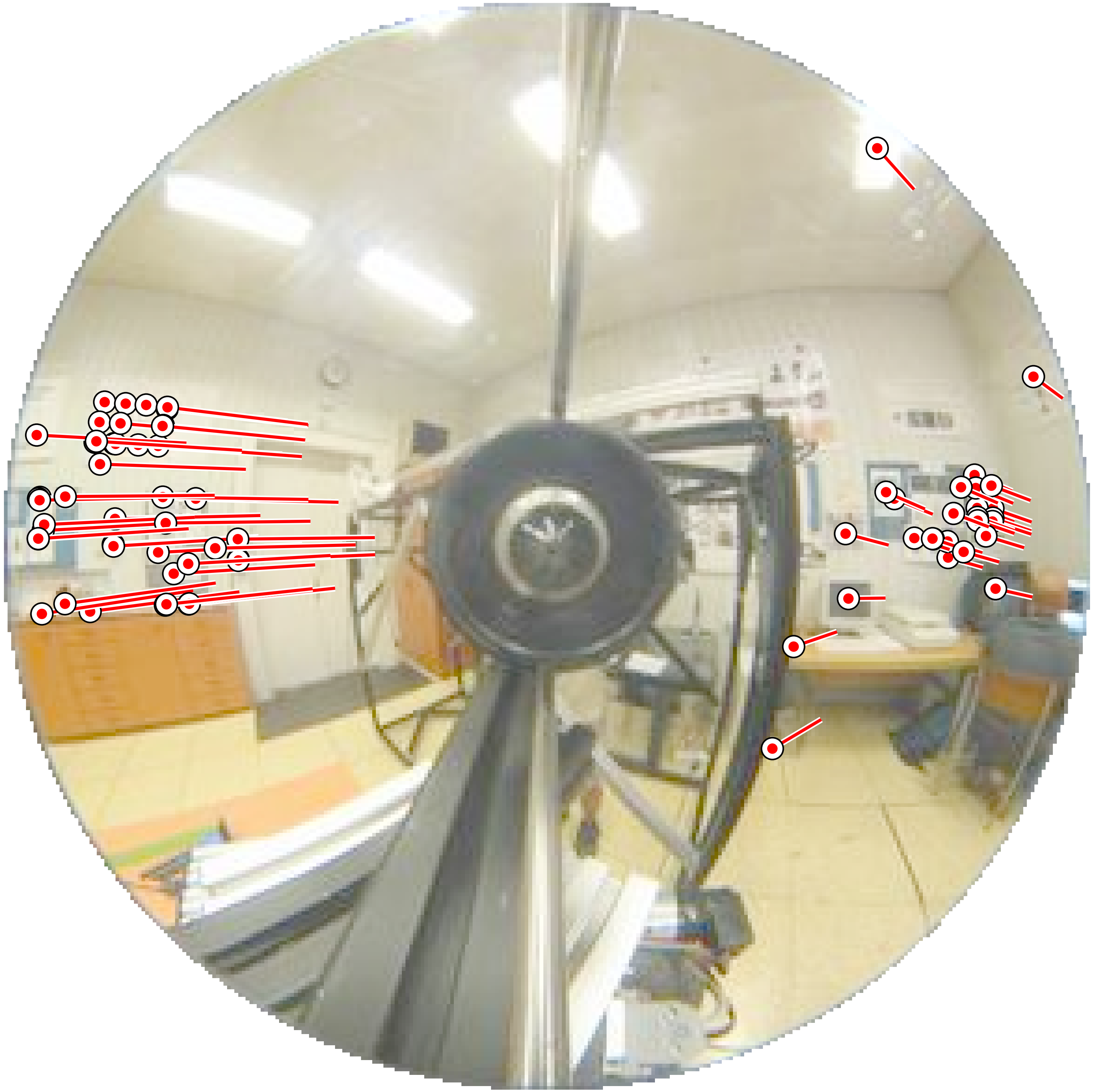

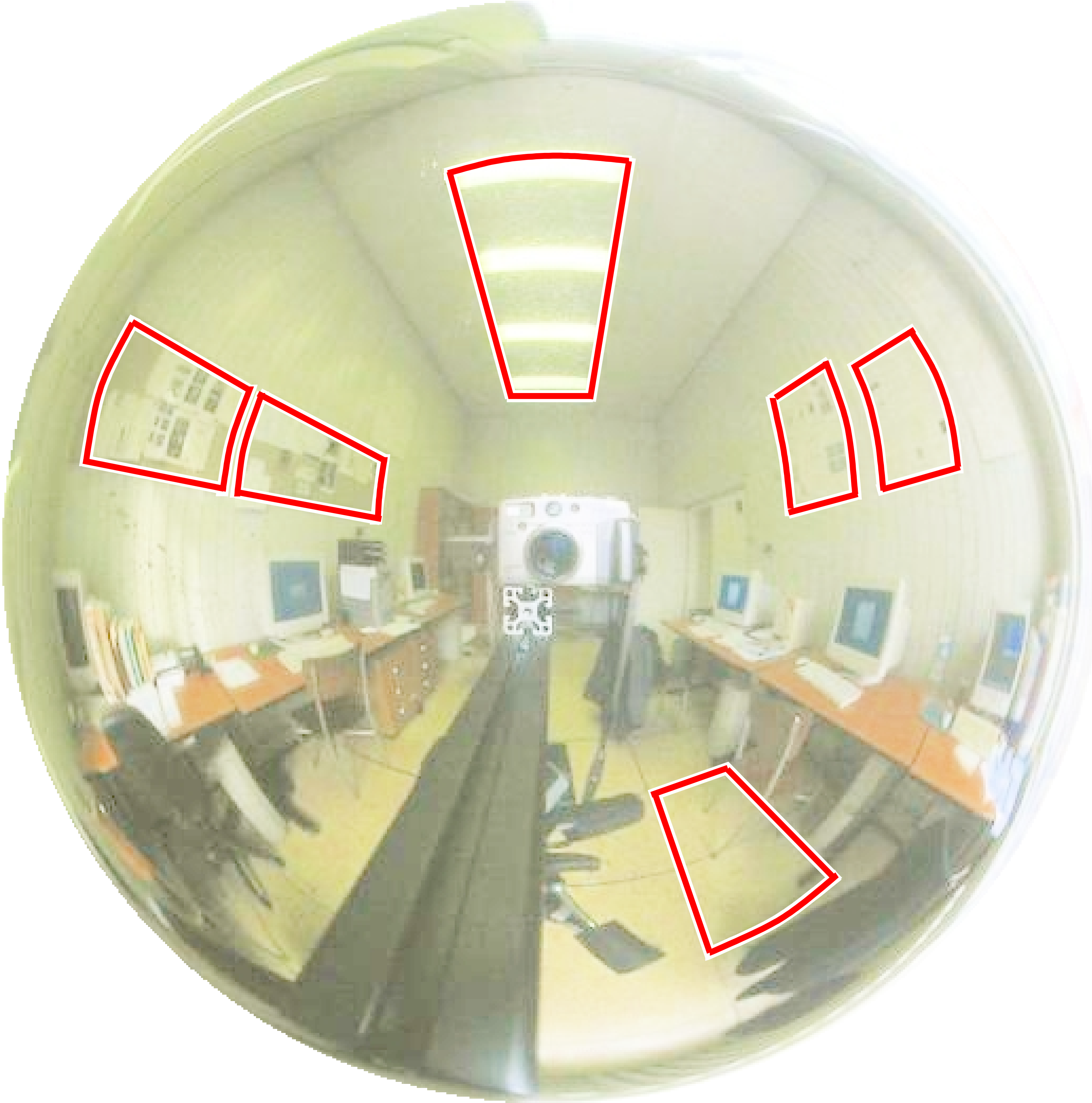

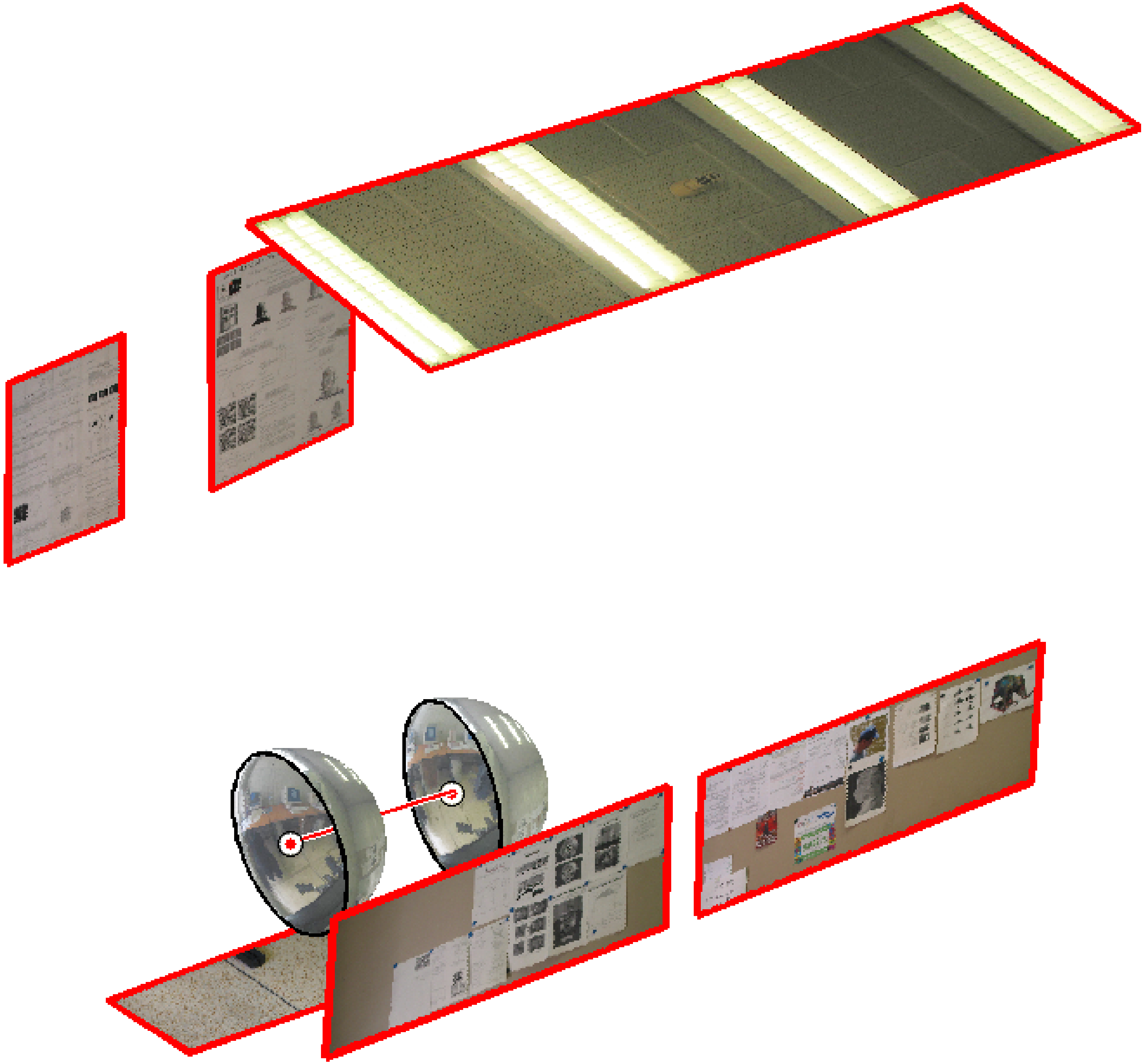

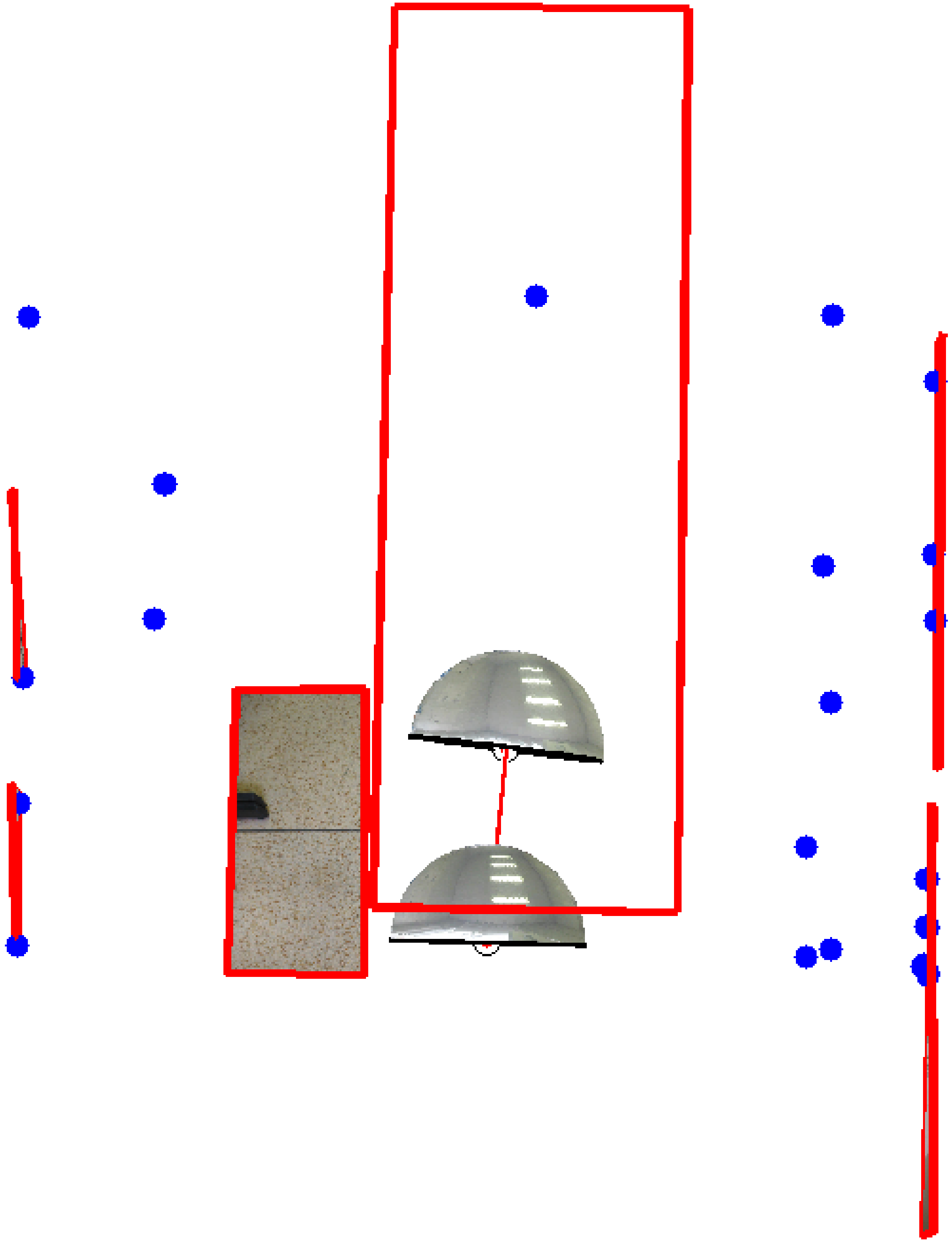

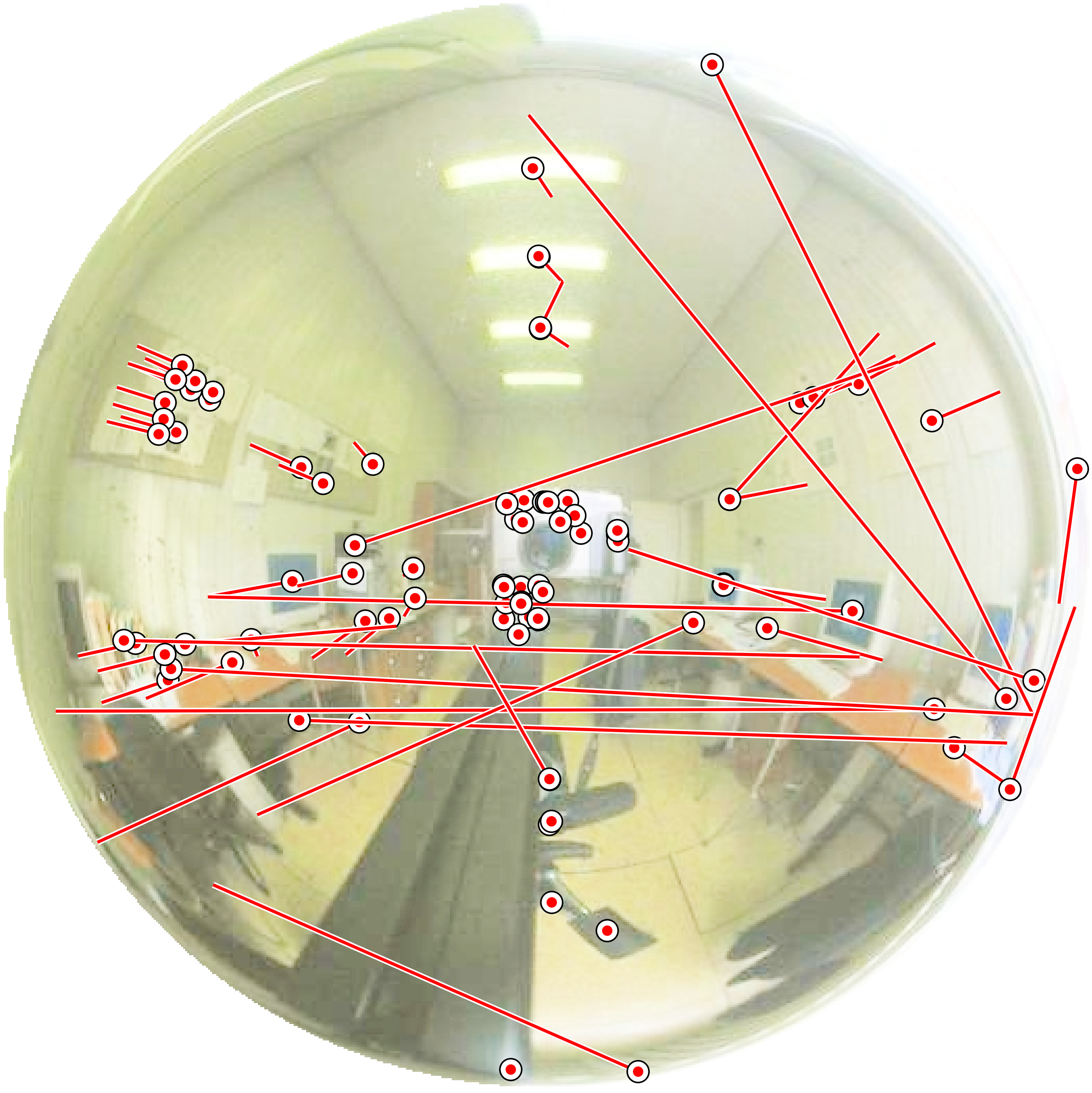

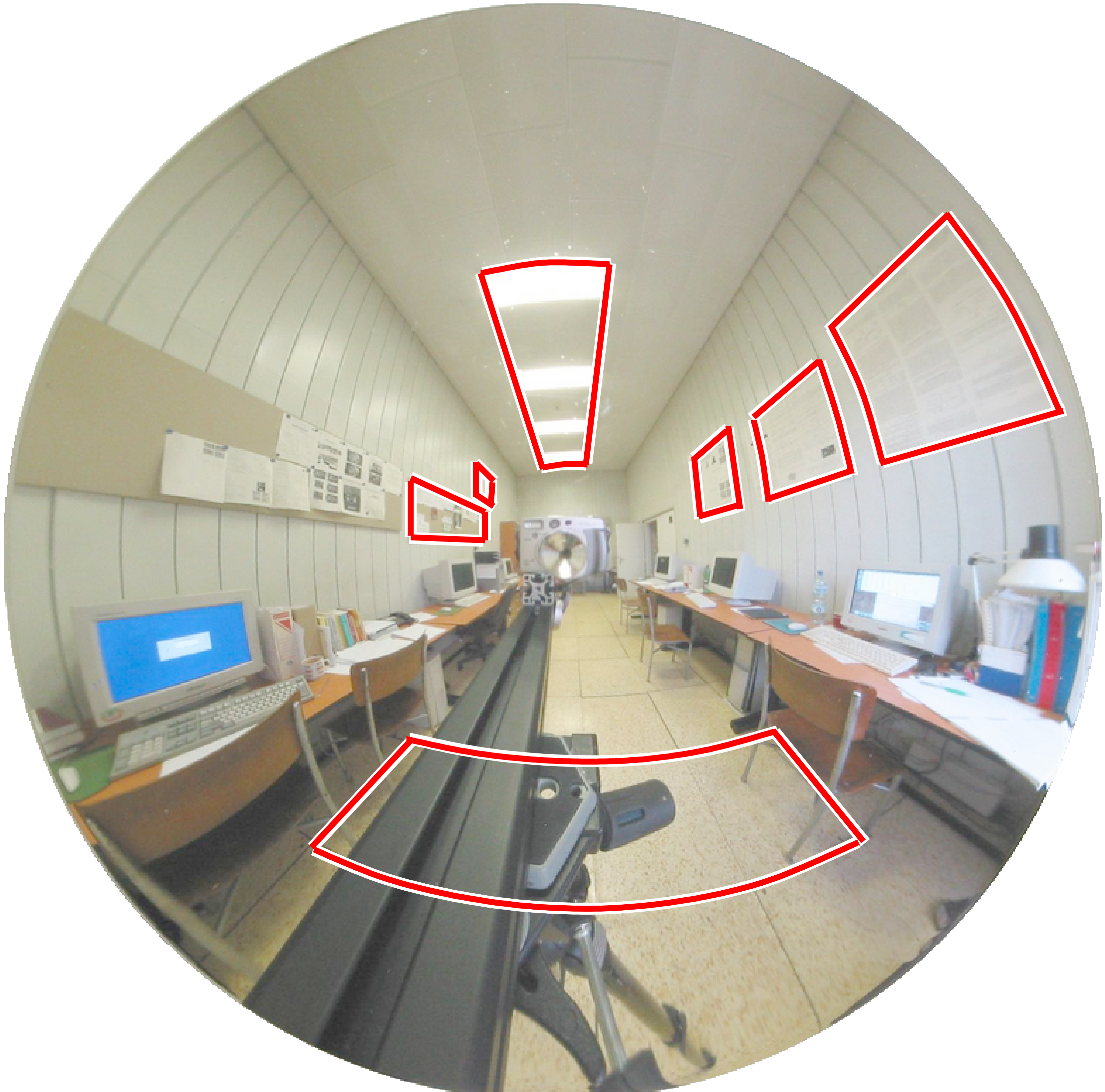

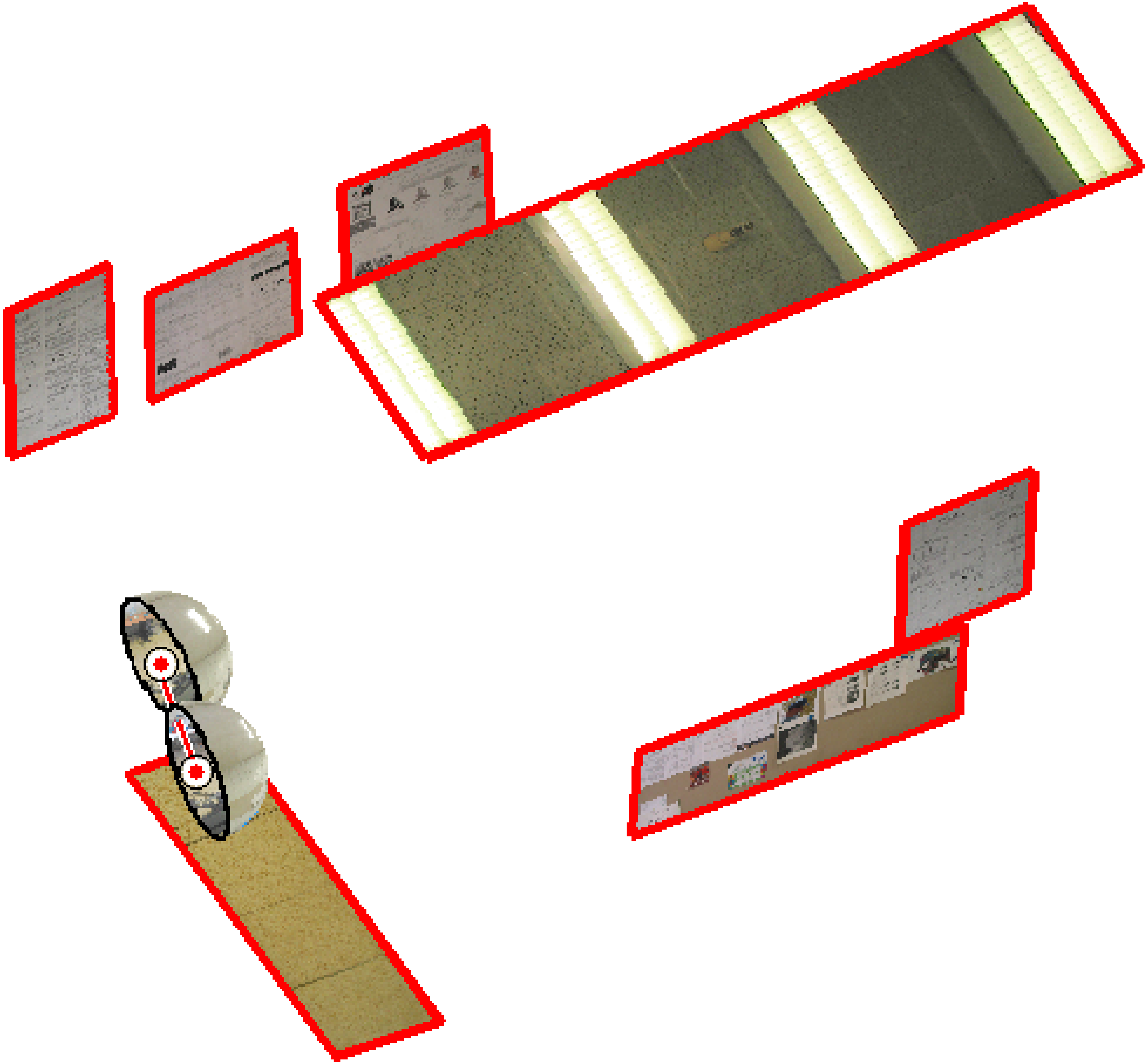

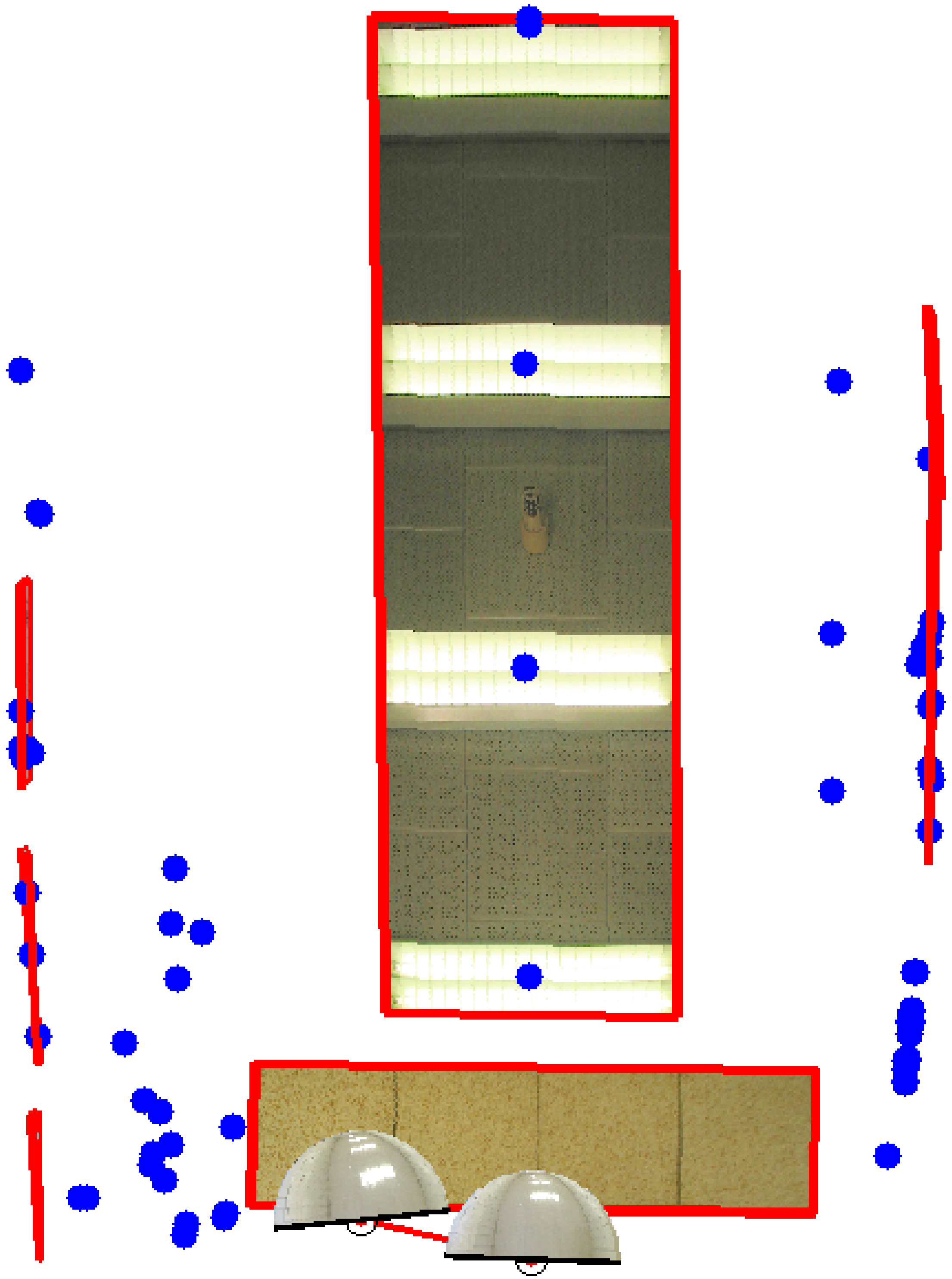

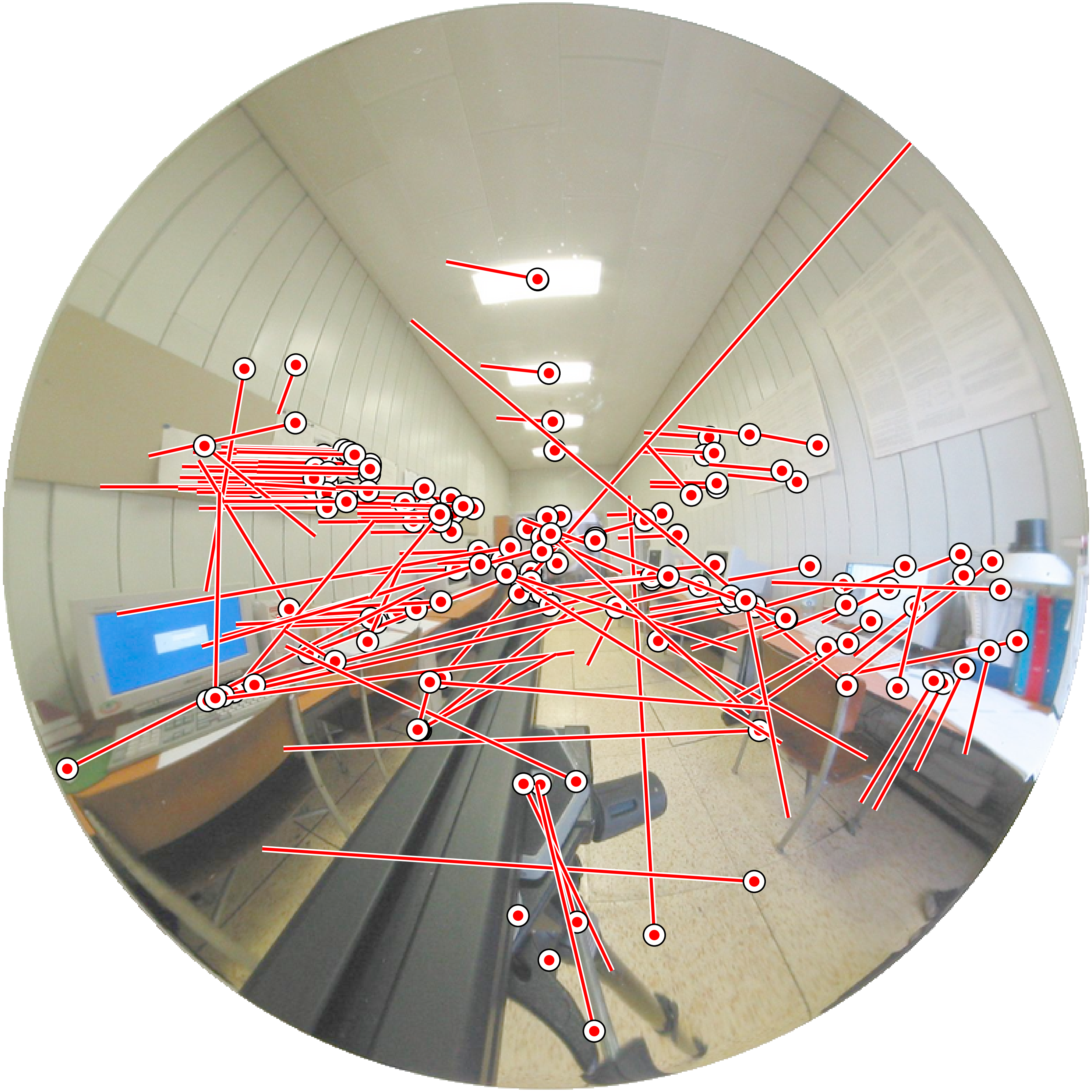

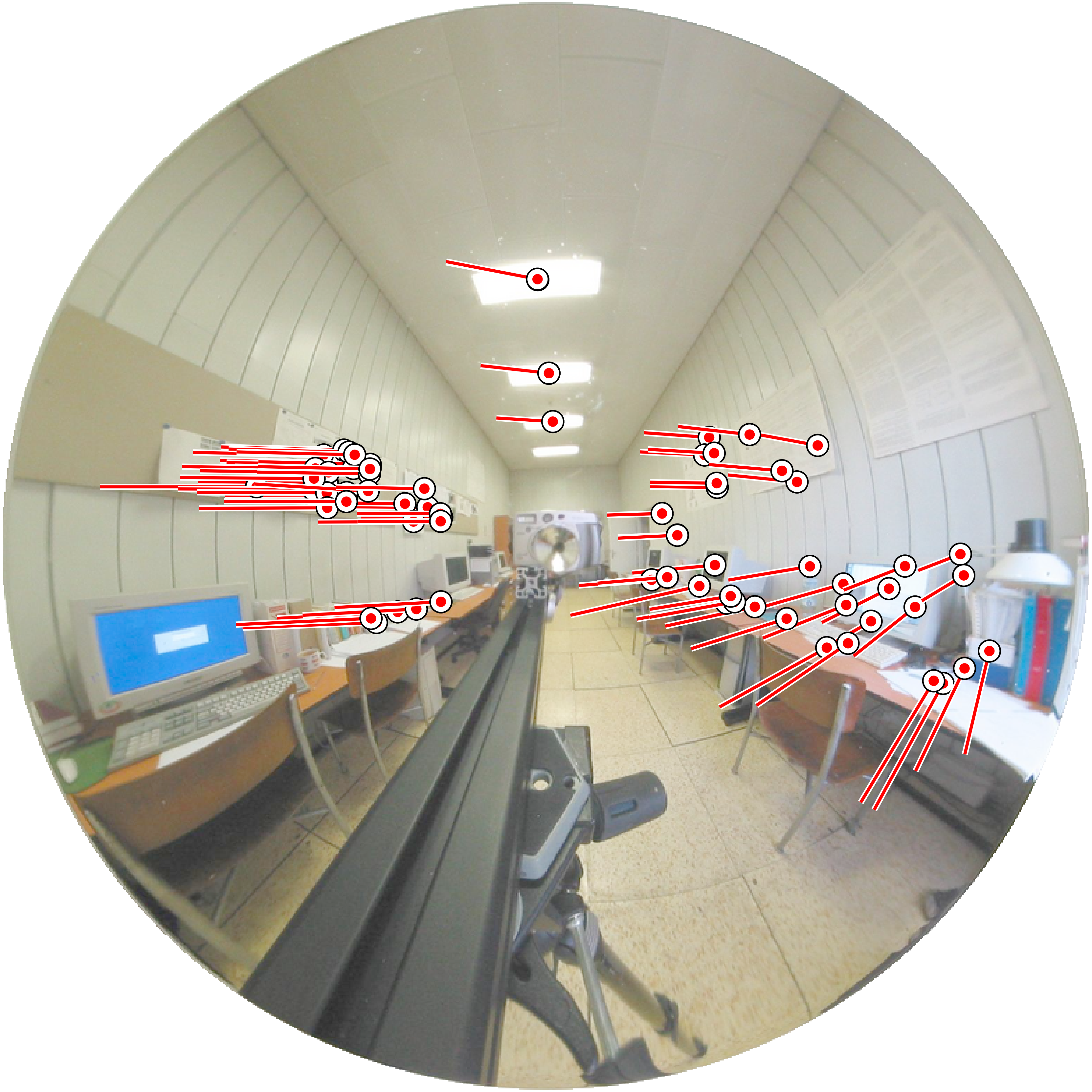

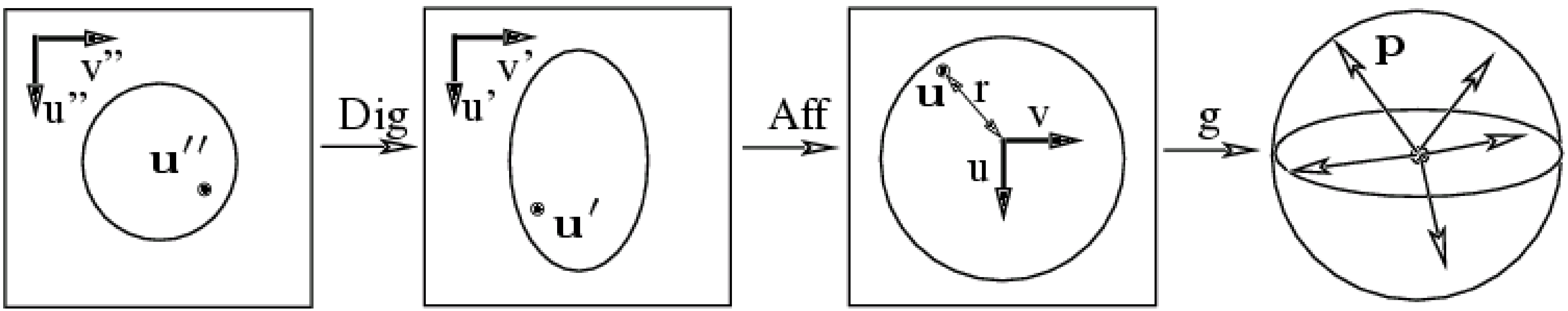
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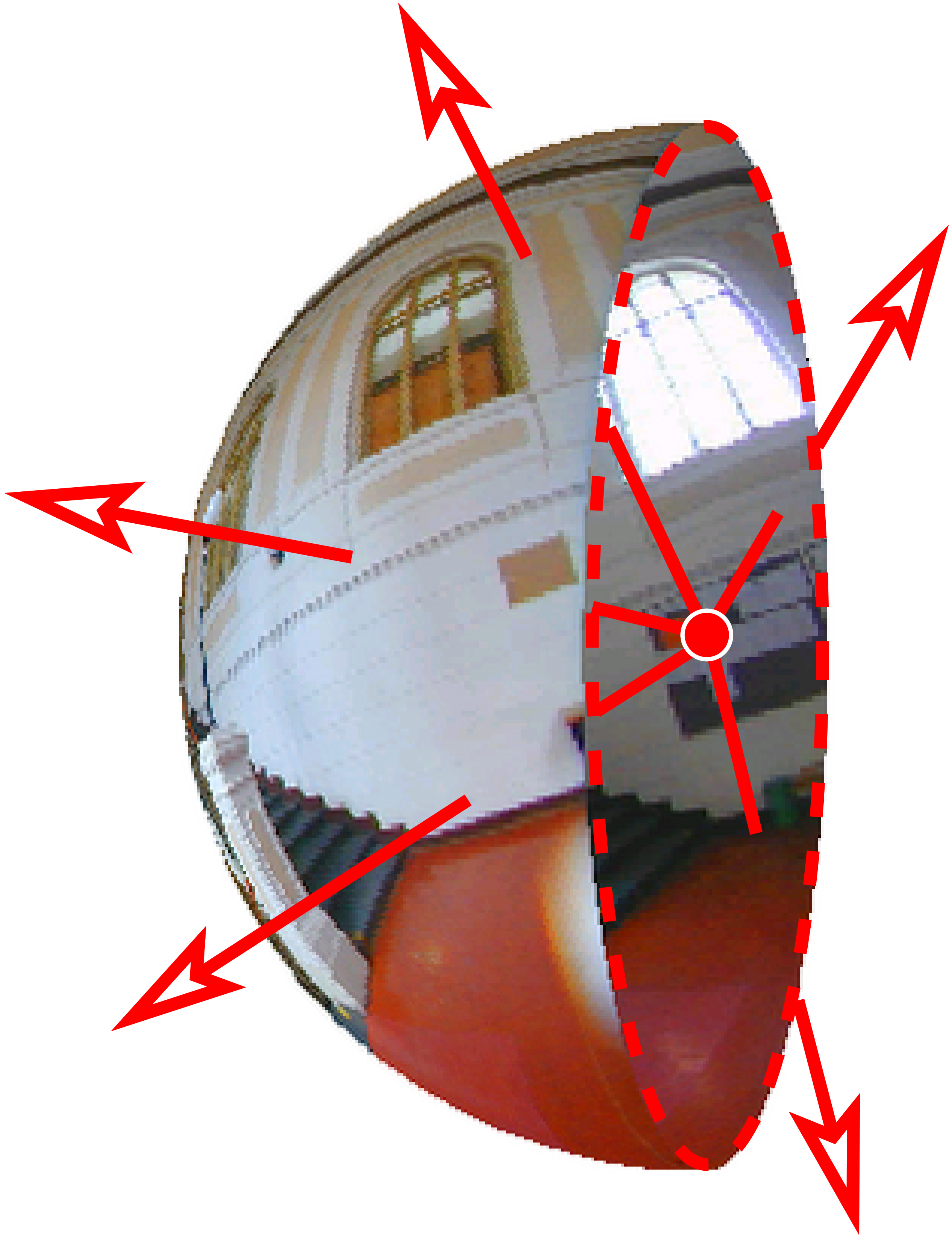

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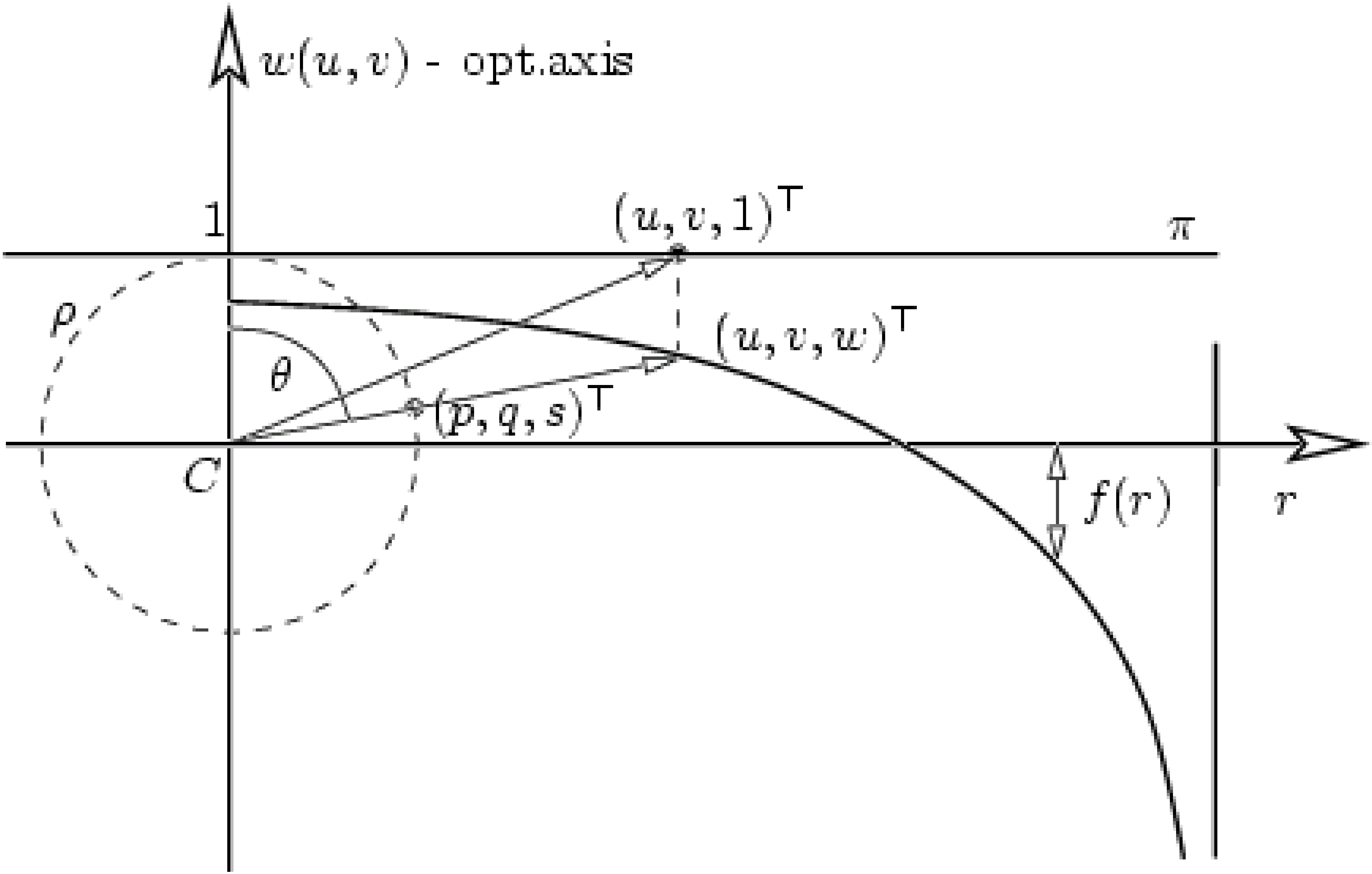

w(u, v) - opt.axis
1
(u, v, 1)⊤
π
ρ
(u, v, w)⊤
θ
(p, q, s)⊤
C
f(r)
r