Omnidirectional vision systems

- Creation of panorama images with one camera
- $360^\circ$ panoramic view and about $30^\circ$ vertical field of view
Introduction

- **Biological inspiration:** Many animals have a wide field of view
- **Example:** Field of view of a fish

- **Problem:** Technical implementation needs special optics
Camera systems with extended field of view

1. Usage of several cameras at once

Problems:

- synchronization necessary
- multiple distortions
- varying colors
- varying brightness (vignetting)
- panorama stitching is content sensitive (fixed mapping table works for far objects - close objects will be mapped wrong)
- solution: depth estimation for each pixel (computationally intensive and not stable)
Example: RingCam (Microsoft Research)

- Five IEEE1394 cameras
- Resolution: 640x480 pixels
- Total resolution: 3000x480 pixels

http://research.microsoft.com/~rcutler/ringcam/ringcam.htm
Camera systems with extended field of view

2. A pivotable or rotating camera

Problems:

- Inaccuracies on rotation around the optical center
- Additional energy consumption for rotation
- Difficult image processing for dynamic scenes
- High computational cost of conversion into a panorama
Camera systems with extended field of view (cont.)

Circular image plane

Camera image planes
Camera systems with extended field of view (cont.)

3. Wide-angle lenses (fisheye lenses)

**Issues:**

- Severe distortion
- Very expensive

4. Convex mirrors with a camera attached below

These omnidirectional vision systems, also known as **catadioptric camera systems**, will be looked at in the following...
Catadioptric camera systems

Combinations of camera, lenses and mirrors are called **catadioptric vision systems**:

- *dioptrics* $\rightarrow$ Lenses
- *catoptrics* $\rightarrow$ Mirrors
Short history of omnidirectional vision systems

1970: U.S. patent by Rees
  ▶ Camera with a hyperboloid mirror

1990: Realtime processing of image data possible
  ▶ Introduction of conical, spherical and hyperbolic mirrors

1997: Theoretical analysis by Nayar and Baker
  ▶ Introduction of a parabolic mirror with a telecentric lens

Detailed history: http://www.math.drexel.edu/~ahicks/design/
Mirror design

(a) Conic mirror

(b) Spherical mirror

(c) Hyperboloidal mirror

(d) Parabolla mirror
Disadvantages of different mirror forms

- In some cases, telecentric lenses need to be used
- The vertical field of view is different
- The full resolution of the camera is not used
- Not every omnidirectional image can be converted into a panorama image with a valid perspective

⇒ In order to produce an image with a correct perspective from a mirror image, a fixed viewpoint is needed
Effective viewpoint

- It seems like one is viewing the scene from this (virtual) viewpoint
- All rays of light which are reflected from the mirror are intersecting in this point
- This position of the viewer corresponds to the hole in a pinpoint camera
- On a camera with a lens system, this point is situated at the rear focal point
Effective viewpoint (cont.)

- On a planar mirror, the effective viewpoint of the viewer lies on the opposite side of the mirror.
- The viewer gets the impression of watching the scene from the effective viewpoint.
- The distance between mirror and observer is the same as the distance between mirror and virtual viewpoint.
Effective viewpoint (cont.)

- If the mirror surface is curved, the tangent plane must be applied to each point of the surface.
- The virtual viewpoint lies on the perpendicular line through the real viewpoint.
Effective viewpoint (cont.)

- As a consequence, several or infinitely many virtual viewpoints result → No image with a correct perspective can be obtained.

- **Please note:** Examples from the field of robotics show that this requirement is not necessary for every application.

- Perspectively correct images are easier to work with for human beings.

- However, through smart mirror construction, one effective viewpoint can be created.
**Fixed Viewpoint Constraint**

**Challenge:** Define a mirror with a surface $z(r)$, that yields one effective viewpoint
Nayar and Baker, 1997:

Mirror shapes resulting from solutions to the following quadratic differential equations have one effective viewpoint

Fixed Viewpoint Constraint

\[ r(c - 2z) \left( \frac{dz}{dr} \right)^2 - 2(r^2 + cz - z^2) \frac{dz}{dr} + r(2z - c) = 0 \]
Generic solution to the Fixed Viewpoint Constraint

\[
(z - \frac{c}{2})^2 - r^2 \left( \frac{k}{2} - 1 \right) = \frac{c^2}{4} (k - 2k) \quad (k \geq 2)
\]

\[
(z - \frac{c}{2})^2 + r^2 \left( 1 + \frac{c^2}{2k} \right) = \left( \frac{2k + c^2}{4} \right) \quad (k > 0)
\]
Specific solutions to the Fixed Viewpoint Constraint

Five solutions:

1. \( k = 2 \) and \( c > 0 \): **Planar mirror**
   \[ z = \frac{c}{2} \]
   ⇒ No omnidirectional images

2. \( k \geq 2 \) and \( c = 0 \): **Conical mirror**
   \[ z = \sqrt{\frac{k-2}{2}} \ r^2 \]
   ⇒ Viewpoint in the apex
Specific solutions to the Fixed Viewpoint Constraint (cont.)

3. $k > 0$ and $c = 0$: **Spheric mirror**
   ⇒ Actual and real viewpoint in the center of the sphere

   $$z^2 + r^2 = k/2$$

4. $k > 0$ and $c > 0$: **Ellipsoidal mirror**
   ⇒ Actual and real viewpoint inside the ellipse

   $$\frac{1}{a_e^2} \left( z - \frac{c}{2} \right)^2 + \frac{1}{b_e^2} r^2 = 1$$

   $$a_e = \sqrt{\frac{2k + c^2}{4}} \quad b_e = \sqrt{\frac{k}{2}}$$
Specific solutions to the Fixed Viewpoint Constraint (cont.)

5. $k > 2$ and $c < 0$: **Hyperboloidal mirror**

$$\frac{1}{a_h^2} \left( z - \frac{c}{2} \right)^2 + \frac{1}{b_h^2} r^2 = 1$$

$$a_h = \frac{c}{2} \sqrt{\frac{k - 2}{k}}$$

$$b_h = \frac{c}{2} \sqrt{\frac{2}{k}}$$
Structure of omnidirectional vision systems

1. **Option:** Mirror is mounted above the camera using a mount

Source: http://cmp.felk.cvut.cz/demos/Omnivis/Photos/fotohyper2.jpg

**Problem:** Mount is always visible in the panoramic image
Structure of omnidirectional vision systems (cont.)

2. **Option:** Mirror is mounted above the camera using a glass cylinder or a glass hemisphere

**Problem:** Reflections on the inner surface of the cylinder/hemisphere

![Diagram showing the setup with a light source and a mirror]
Structure of omnidirectional vision systems (cont.)

Omnidirectional shot:
With reflections on the left, without reflections on the right
Creator of hyperboloidal mirrors

- PANORAMA EYE®: Seiwapro Co., Ltd.,
  http://www.accowle.com/englisch/

- "Mirror-Lens" Single-Shot Panorama optics:
  Panorama-Hardware, Hamburg, Germany
  http://www.panorama-hardware.de
Panorama calculation

Two procedures for conversion into a panorama image are available

- **Simple direct conversion**
  
The image from the omnidirectional vision system is evenly sampled

- **Hyperboloidal projection**
  
A panorama projection is a projection on a cylinder around the mirror
Simple conversion

For example with the free software *PUT* by www.panorama-hardware.de
Simple conversion (cont.)

For a panorama of the size \( width \times height \), each pixel needs to be determined through the corresponding pixel in the omnidirectional image

\[
\text{Image createPanorama (int width, int height, Image omni)}
\]

\[
\{
    \text{Image panorama = new Image (width, height);} \\
    \text{for (int i=0; i<width; i++) } \\
    \quad \text{for (int j=0; j<height; j++) } \\
    \quad \quad \text{panorama.setPixel} \\
    \quad \quad \quad (i, j, \text{getPixelFromOmnidirectional (i, j, omni)}); \\
\}
\]
Simple conversion (cont.)

```cpp
Pixel getPixelFromOmnidirectional (int i, int j, Image omni) {
    // calculation of polar coordinates
    double radius = outerRing -
        ((j/height) * (outerRing-innerRing));
    double alpha = - (i/width) * (2*PI);

    // coordinates in the omnidirectional image
    double x = centerX - radius * sin(alpha);
    double y = centerY + radius * cos(alpha);

    // return interpolated pixel
    return omni.getInterpolatedPixel (x, y);
}
```
Hyperboloidal projection
Reduction to 2D-problem
Reduction to 2D-problem (cont.)

Hyperbola-equation:

\[ \frac{R^2}{a^2} - \frac{Z^2}{b^2} = -1 \]

\[ c = \sqrt{a^2 + b^2} \]
Hyperboloidal projection

Basically, two steps are necessary (nach Yamazawa et. al., 1993)

1. Projection of a cylinder point onto the mirror surface
2. Projection of the mirror surface onto the image area

\[ r = f \cdot \tan(\beta) \]
\[ \beta = \tan^{-1} \left( \frac{(b^2 + c^2) \cos(\alpha) - 2bc}{(b^2 - c^2) \cos(\alpha)} \right) \]
\[ \alpha = \tan^{-1} \left( \frac{(b^2 + c^2) \cos(\beta) - 2bc}{(b^2 - c^2) \cos(\beta)} \right) \]
\[ \alpha = \frac{R}{Z - c} \]
Camera calibration

In order to perform the hyperboloidal projection, a calibration of the camera is necessary:

- **Known:** $a$ and $b$ of hyperbola and mirror diameter
- **To be calculated:** extrinsic parameters (translation and rotation between mirror and calibration object) and intrinsic parameters (focal length, distortion coefficients and principal point)

For calibration, there’s a MATLAB-Toolkit:
http://www.vision.caltech.edu/bouguetj/calib_doc/htmls/links.html
Literature list

Uncalibrated stereo vision with pointing for a man-machine interface.

A versatile camera calibration technique for 3d machine vision metrology using off-the-shelf tv cameras and lenses.