Open Source Computer Vision Library

Victor Eruhimov

ITSEEZ

Microsoft Computer Vision School

itseez

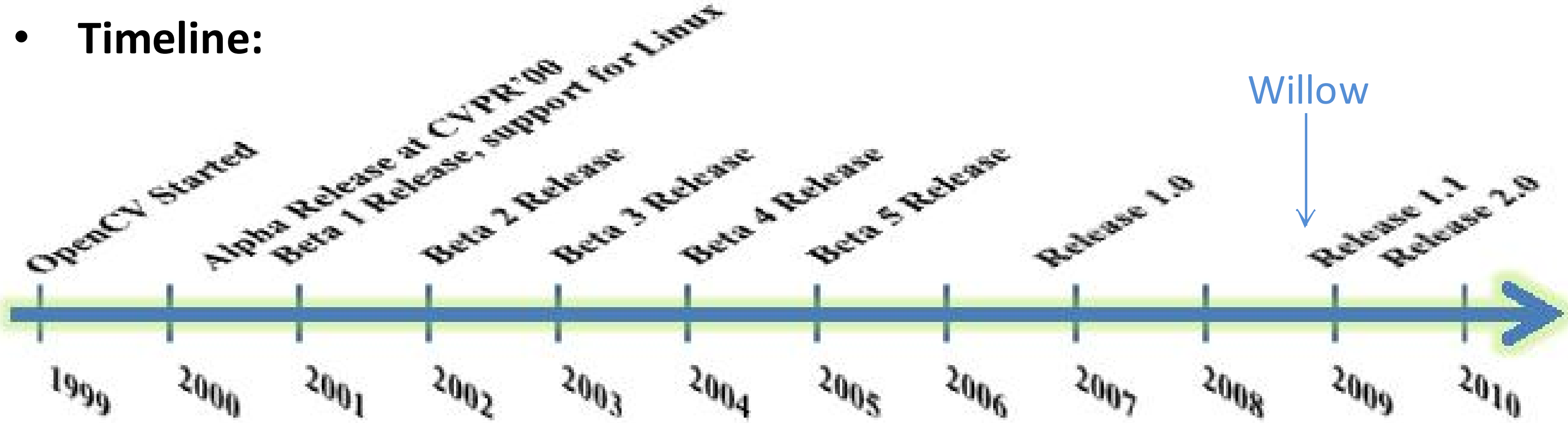
OpenCV

Outline

- Functionality
- Programming with OpenCV
- OpenCV on CPU & GPU
- Mobile vision

OpenCV History

- **Original goal:**
  - Accelerate the field by lowering the bar to computer vision
  - Find compelling uses for the increasing MIPS out in the market
- **Timeline:**



- **Staffing:**
  - Climbed in 1999 to average 7 first couple of years
  - Starting 2003 support declined between zero and one with exception of transferring the machine learning from manufacturing work I led (equivalent of 3 people).
  - Support to zero the couple of years before Willow.
  - 5 people over the last year

OpenCV Functionality Overview

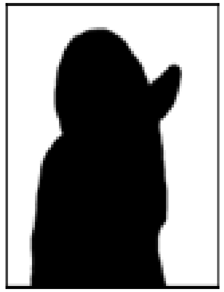
Image processing

•General Image Processing

Transforms

Fitting

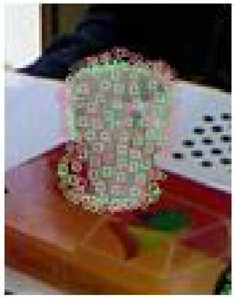
Optical Flow



Segmentation

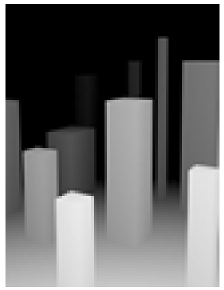
Video, Stereo, and 3D

Camera Calibration



Pose estimation

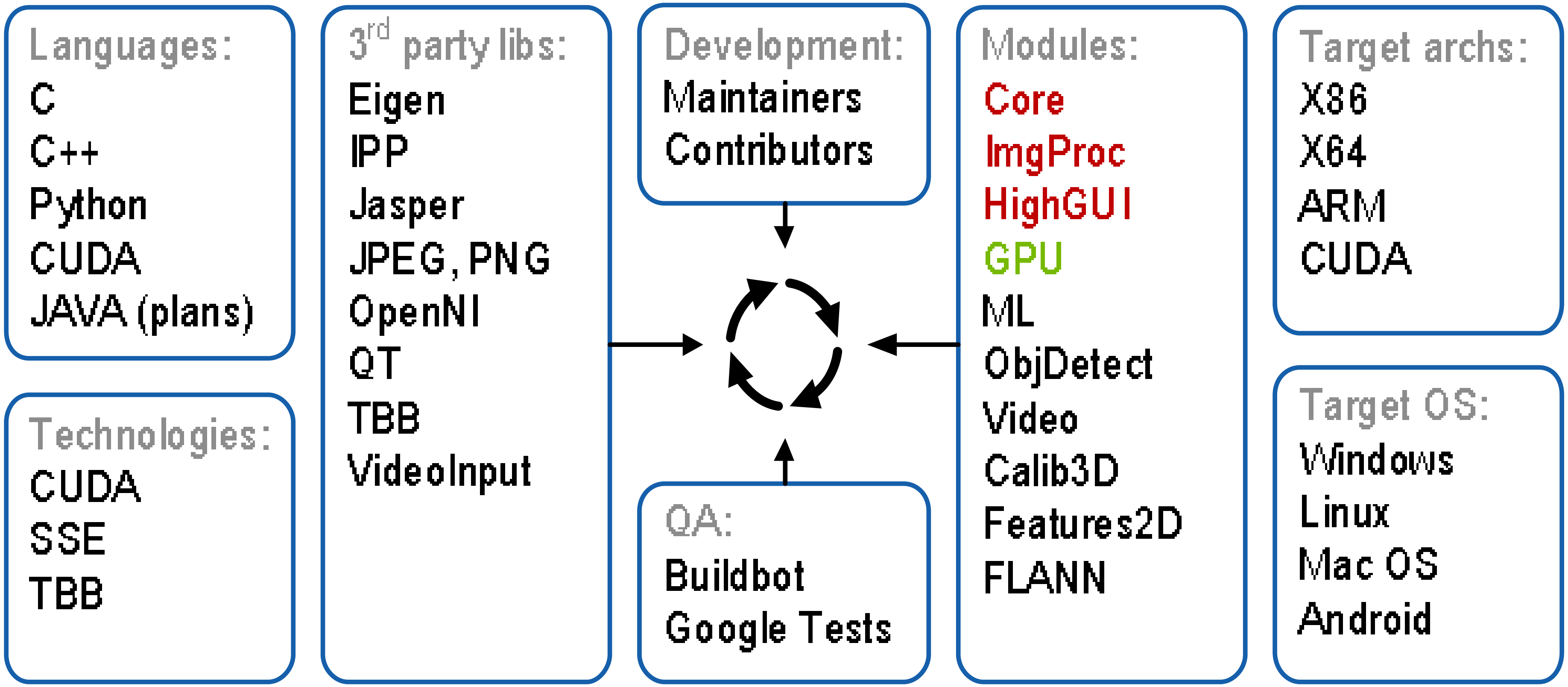
Features



Depth Maps

Object detection

OpenCV Architecture and Development



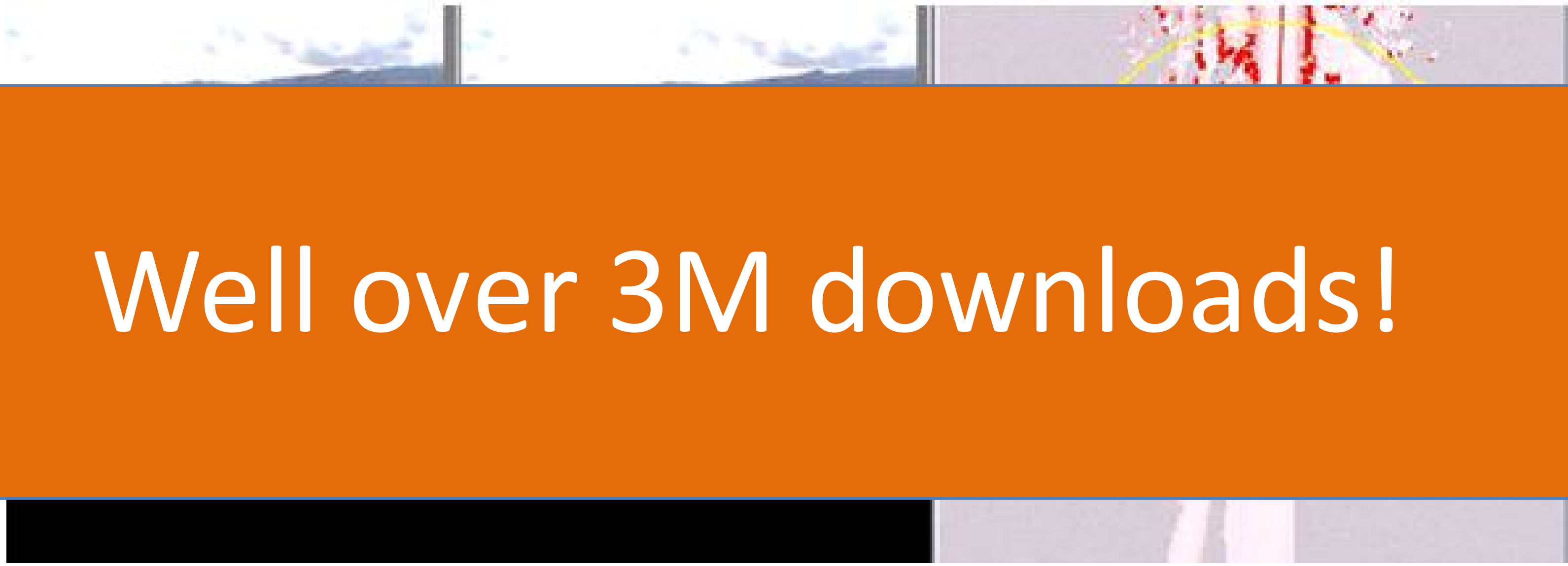
OpenCV License

- Based on BSD license
- Free for commercial and research use
- Does not force your code to be open
- You need not contribute back
  - But you are very welcome to contribute back!

OpenCV sponsors

Where is OpenCV Used?

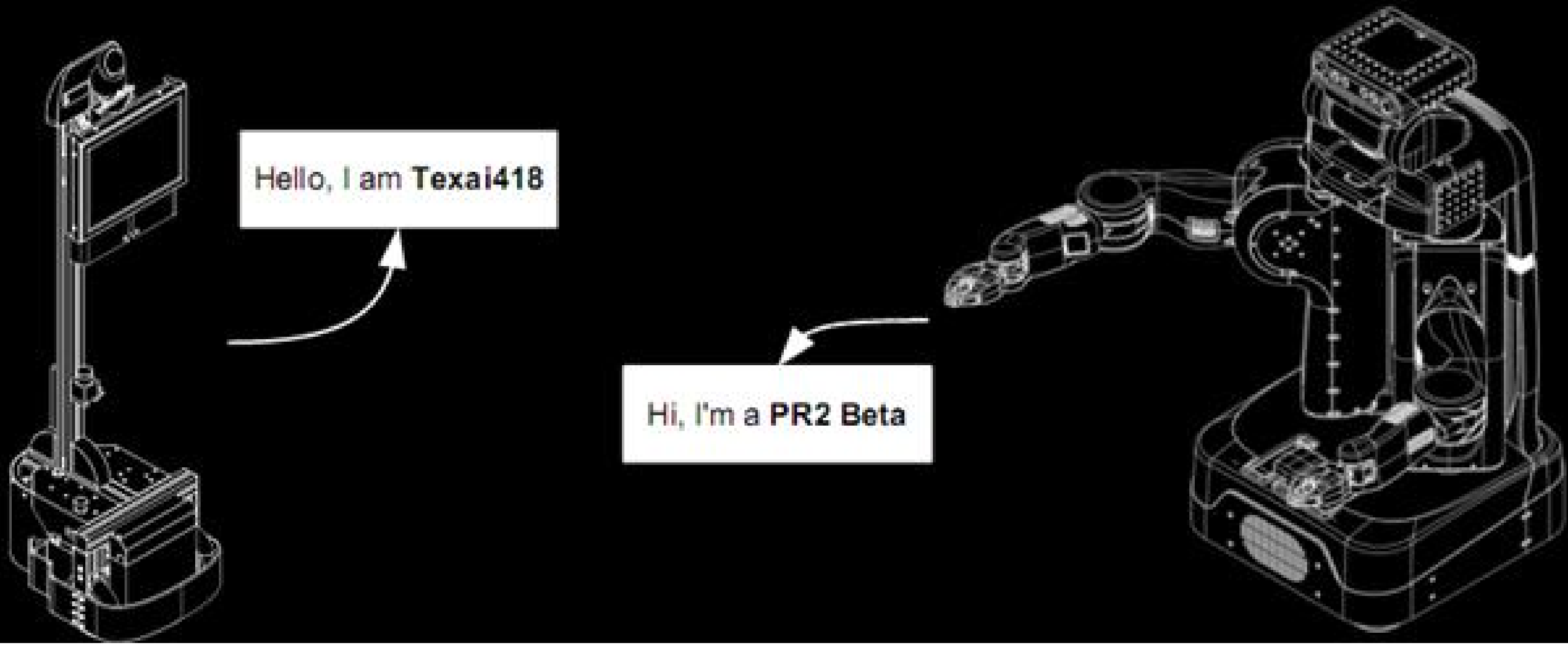
- Academic and Industry Research
- Security systems
- Image/video search and retrieval
- Structure from motion in movies
- Machine vision factory production inspection systems
- Automatic Driver Assistance Systems
- Safety monitoring (Dam sites, mines, swimming pools)
- Robotics



Well over 3M downloads!

Robotics Operation System

- Meta operating system for robotics
- Obtain, build, write, and run code across multiple computers, and multiple robots



Usage examples: ROS

- Imagery infrastructure
- Camera calibration
- Object detection
- Pose estimation
- Human awareness

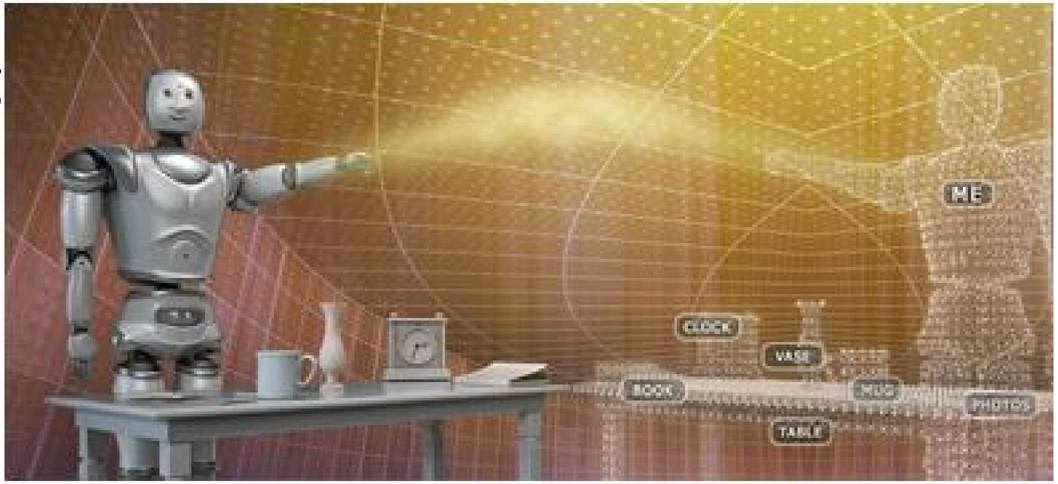
Hackathons

poolshark

Complete Run

3D Processing: PCL

- Point Cloud Library
  - http://pointclouds.org



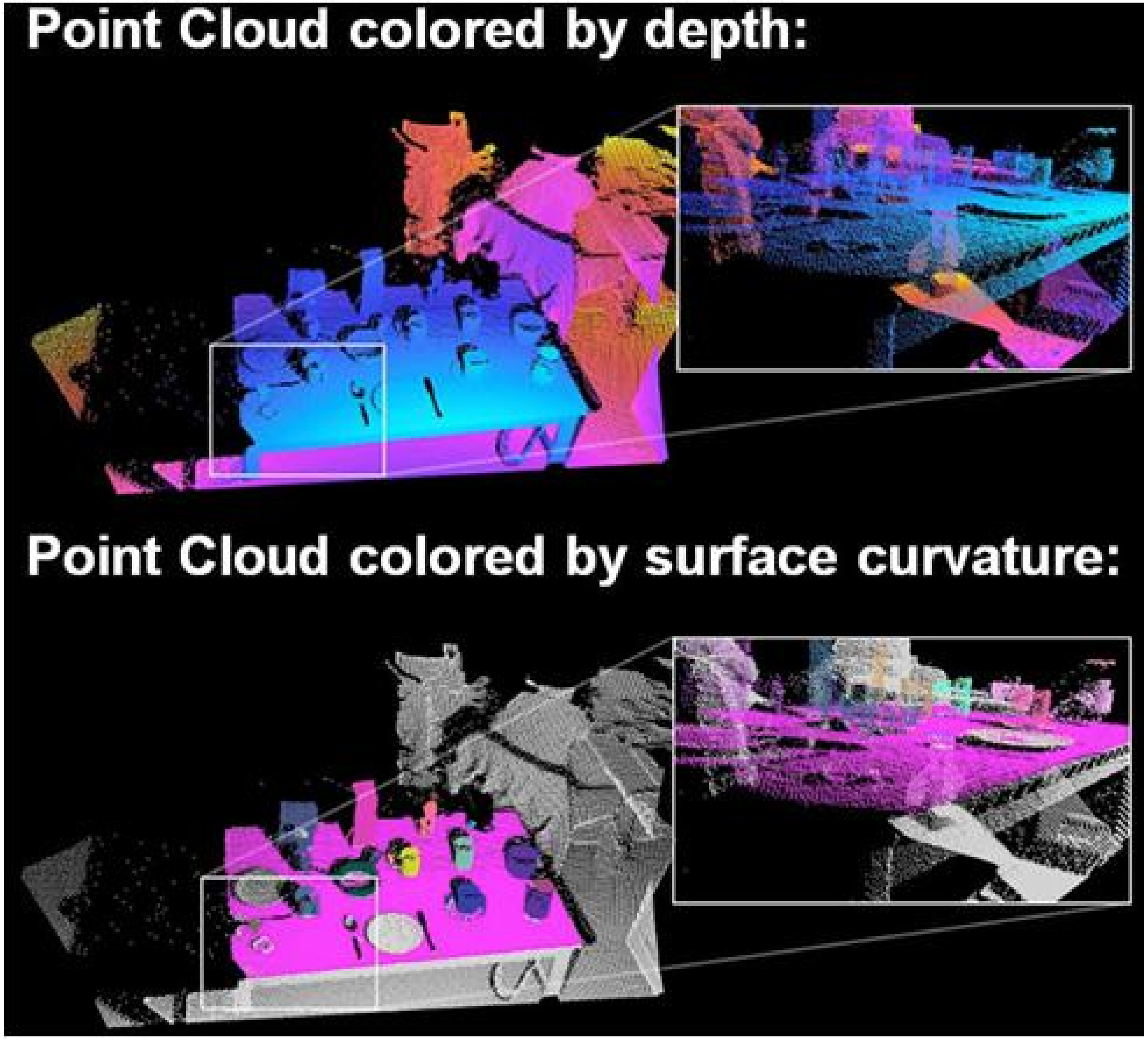
Misc, stats:

- 35 releases already (0.1.x $\rightarrow$ 0.9.9)
- over 100 classes
- over 80k lines of code (PCL, ROS interface, Visualization)
- young library: only 12 months of development so far, but we had code lying around for 3-5 years
- external dependencies on eigen, cminpack, FLANN

PCL: Finding Normals

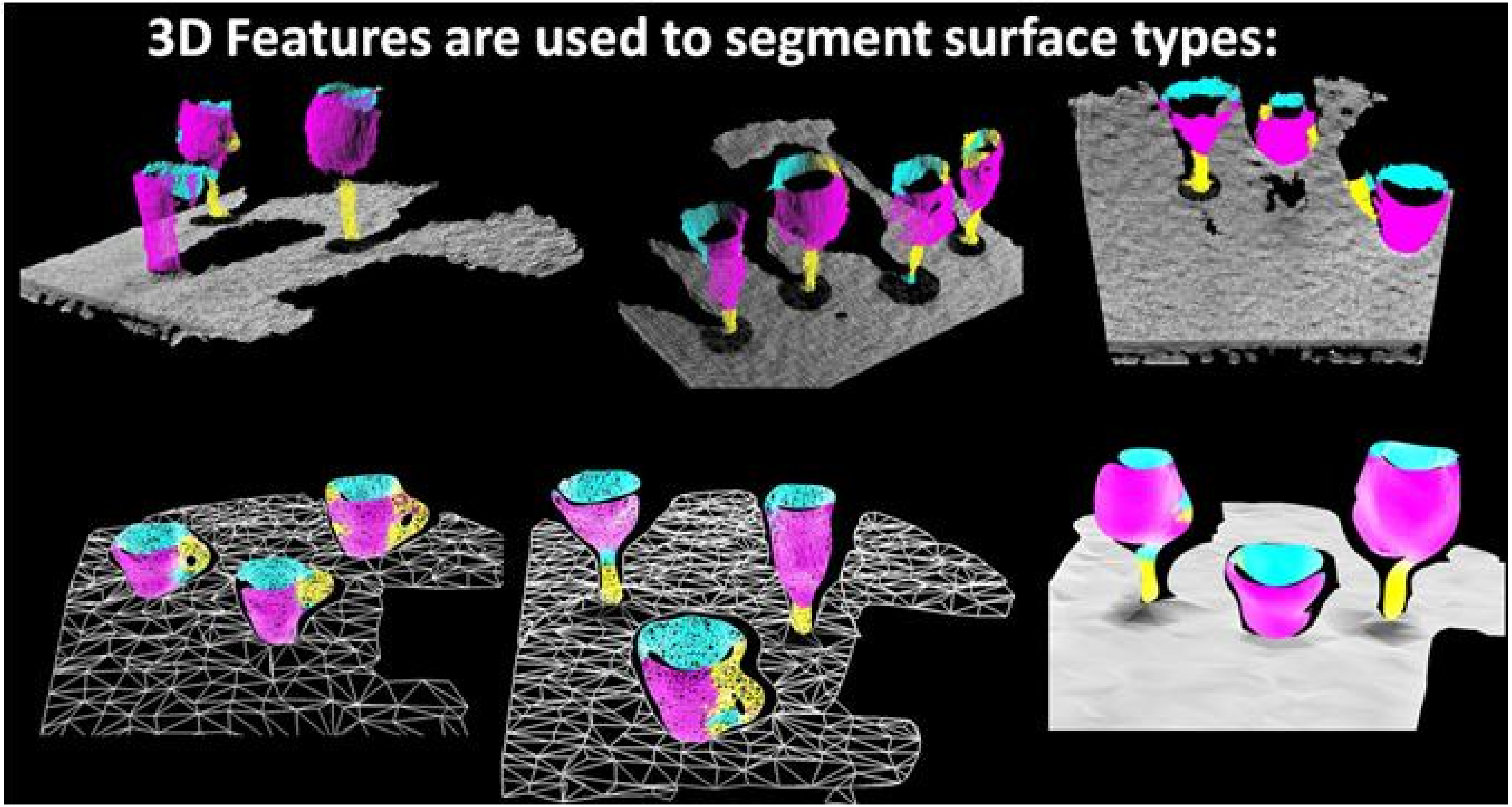
```
p.setInputCloud (data);
p.setInputNormals (normals);
p.SetRadiusSearch (0.01);
```

PCL: Filtering by surface curvature



PCL:

Using 3D features to classify surface types



OpenCV Czar

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- Mobile vision

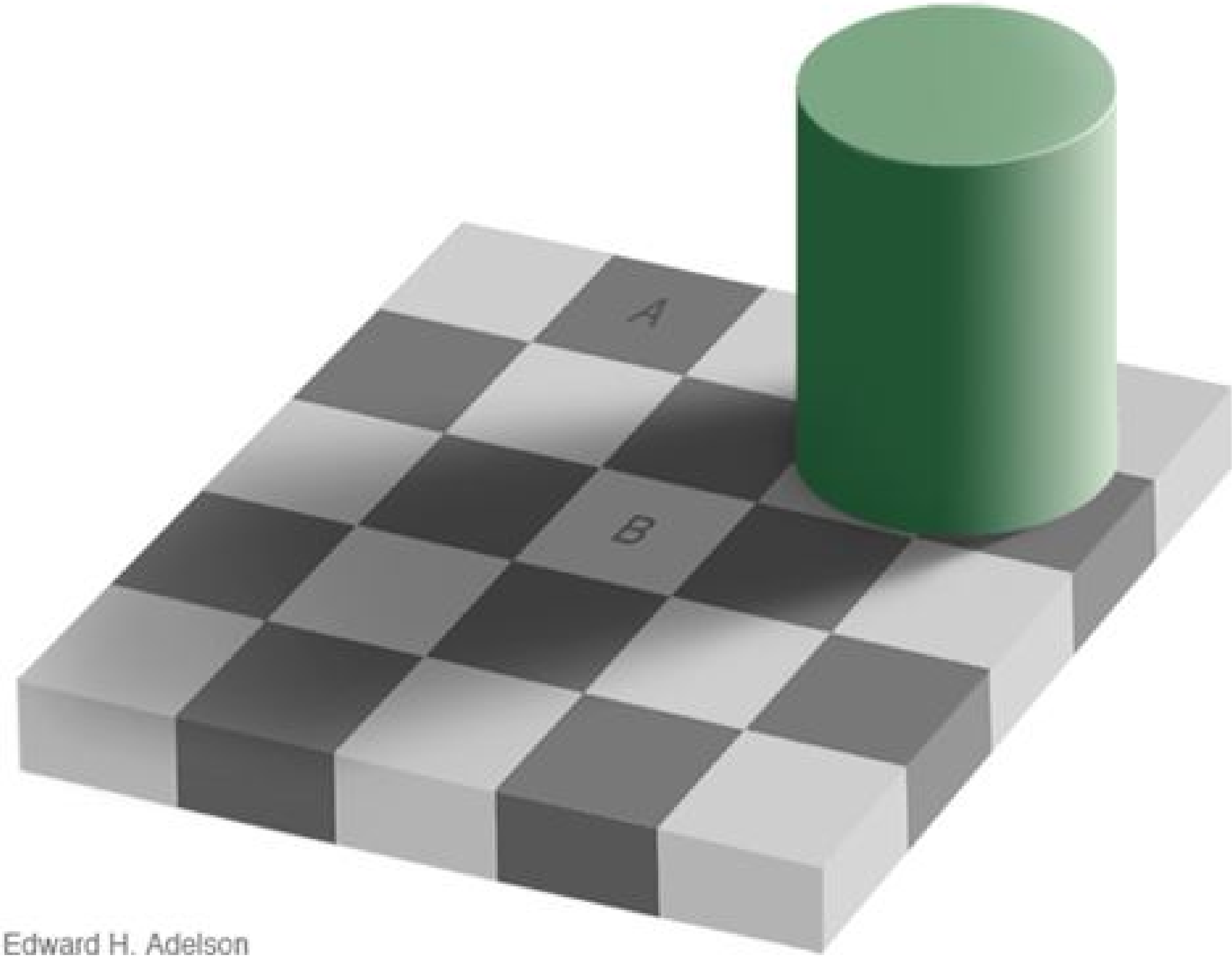
How to choose which algorithms to put into the library?

- Well established
- Works on any data
  - Productized by a commercial company
  - Patented
- Easy to reproduce

VS

- Cutting edge
- Works on Lenna only
- Have to hallucinate the missing pieces
  - And then it works on Lenna only


© 2007 Kurt Wenner



Edward H. Adelson

Imgproc 1

General Image Processing Functions

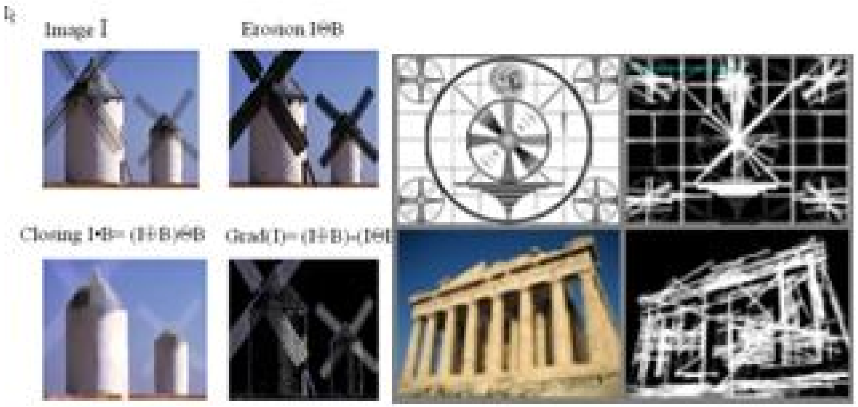
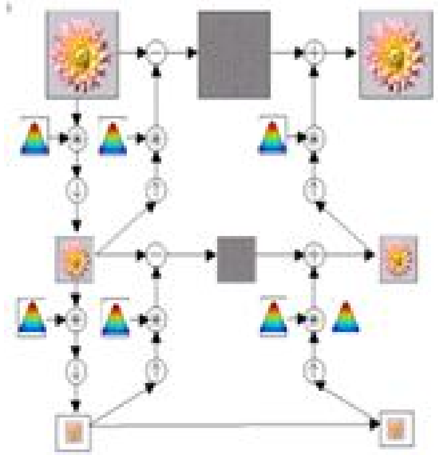
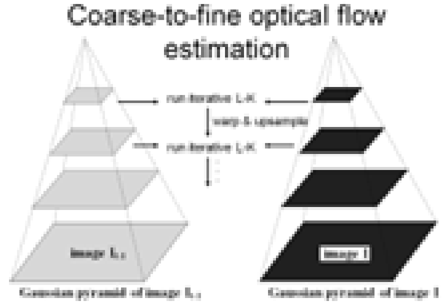
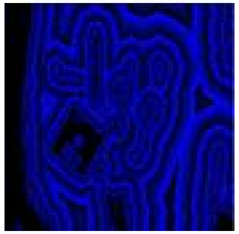


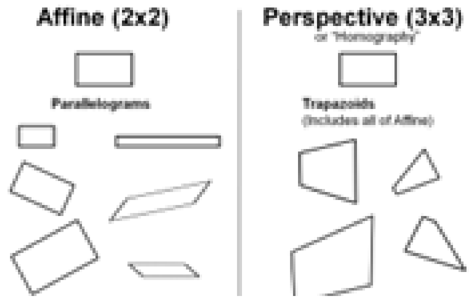
Image Pyramids

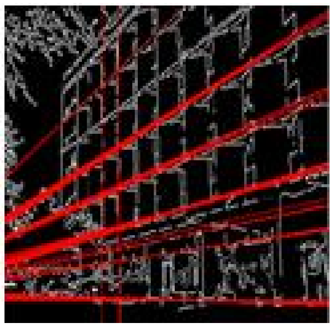




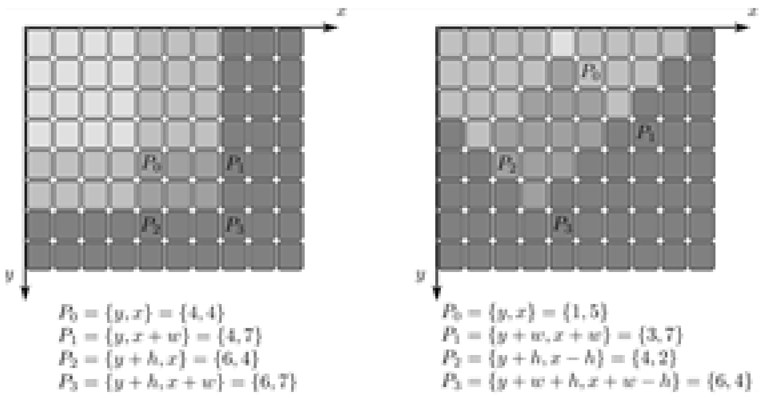
Transforms







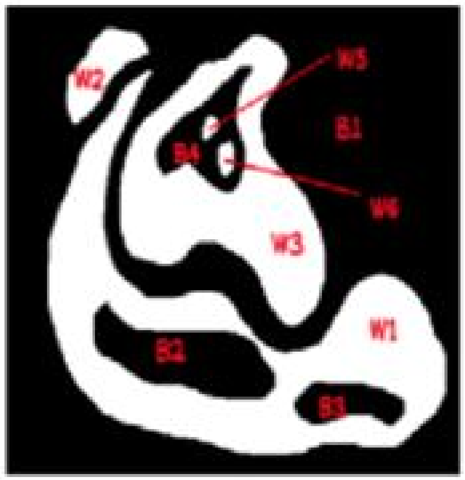
Integral images

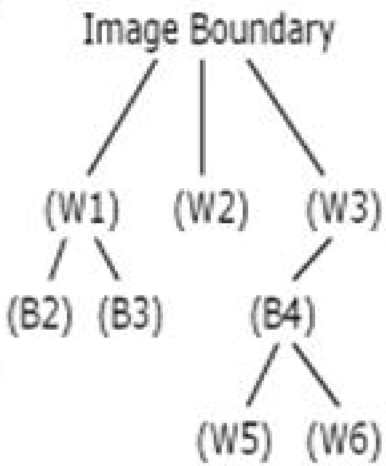


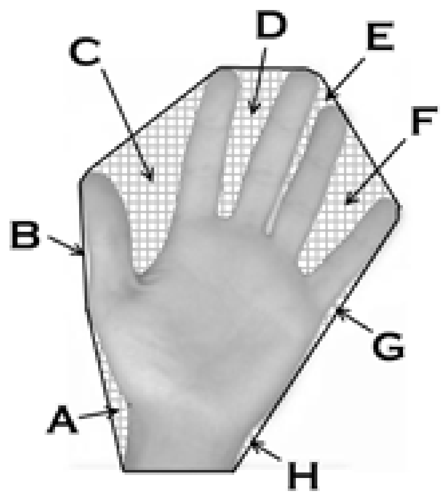
Imgproc 2

Segmentation

Shape analysis

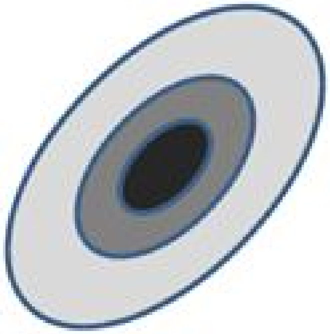






Features2d contents

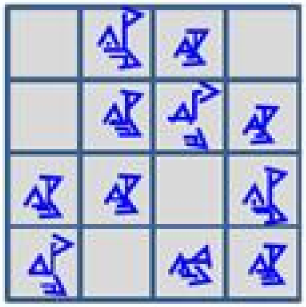
Detection



Detectors available

- SIFT
- SURF
- FAST
- STAR
- MSER
- HARRIS
- GFTT (Good Features To Track)

Description



Descriptors available

- SIFT
- SURF
- Calonder
- Ferns
- One way
- HoG

Matching

Matchers available

- BruteForce
- FlannBased
- BOW

Matches filters

(under construction)

- Cross check
- Ratio check

Detector testbench

- Measures of detector repeatability are taken from
  - K.Mikolajczyk, Cordelia Schmid, “Scale & Affine Invariant Interest Point Detectors”, IJCV 60(1), 63–86, 2004.
  - K.Mikolajczyk et al, A Comparison of Affine Region Detectors, IJCV 65(1/2):43-72, 2005.
- Test images are taken from http://www.robots.ox.ac.uk/~vgg/data/data-aff.html
- Testbench is located in opencv_extra/testdata/cv/detectors_descriptors_evaluation/detectors

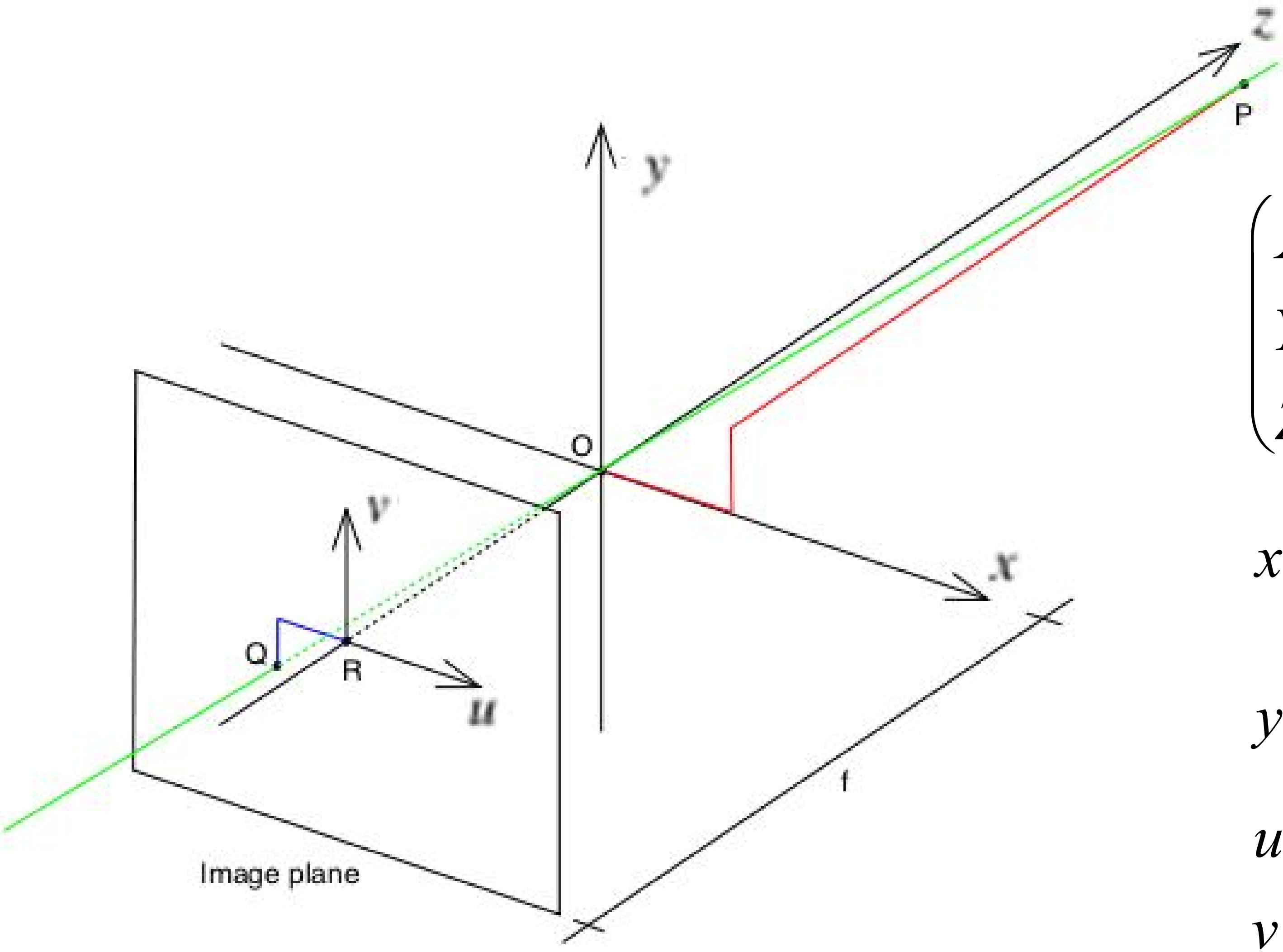
Descriptor testbench

- Measures of descriptor matching accuracy are taken from
  http://www.robots.ox.ac.uk/~vgg/research/affine/det_eval_files/mikolajczyk_pami2004.pdf
- Test images are taken from http://www.robots.ox.ac.uk/~vgg/data/data-aff.html
- Testbench is located in opencv_extra/testdata/cv/detectors_descriptors_evaluation/descriptors

Calib3d module

- Camera calibration
- 3D -> 2D projection
- Homography in 2D and 3D
- PnP problem solver
- Stereo vision
- Fundamental matrix
- Template detectors

Pinhole camera model



$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = R \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} + t$$

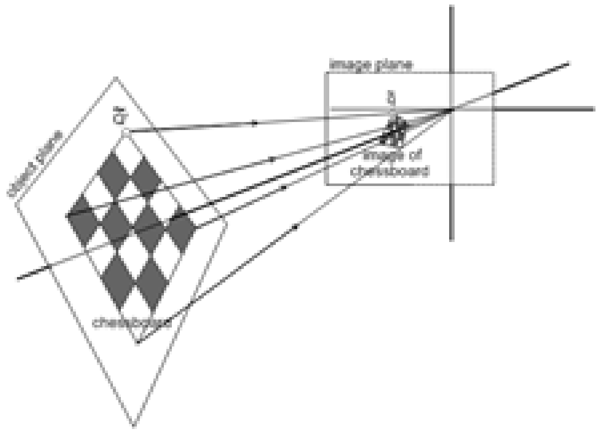
$$x' = \frac{X}{Z}$$

$$y' = \frac{Y}{Z}$$

$$u = f_x x' + c_x$$

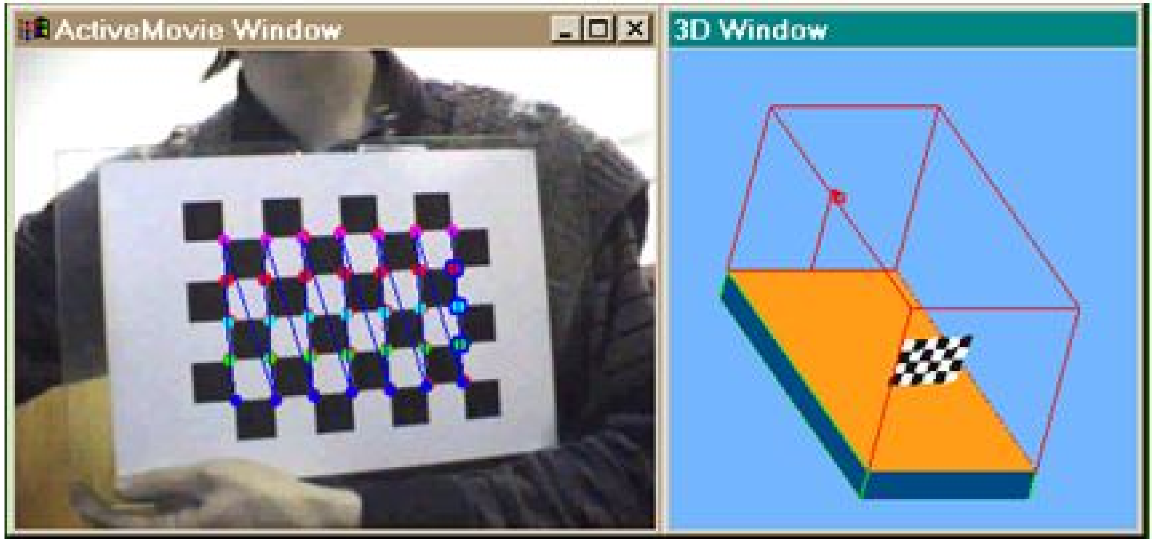
$$v = f_y y' + c_y$$

Camera Calibration



See samples/cpp/calibration.cpp

3D view of checkerboard

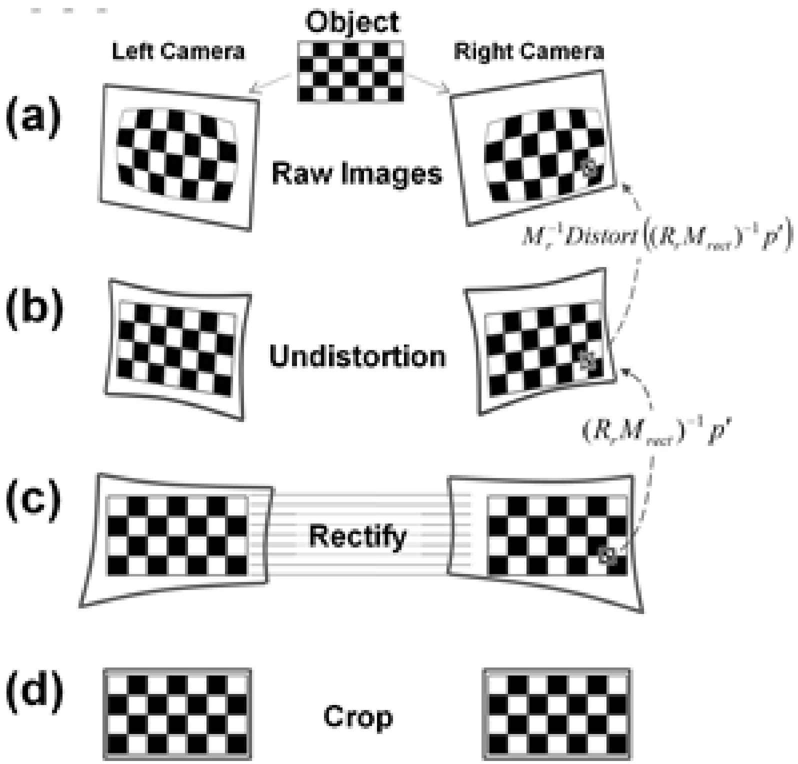


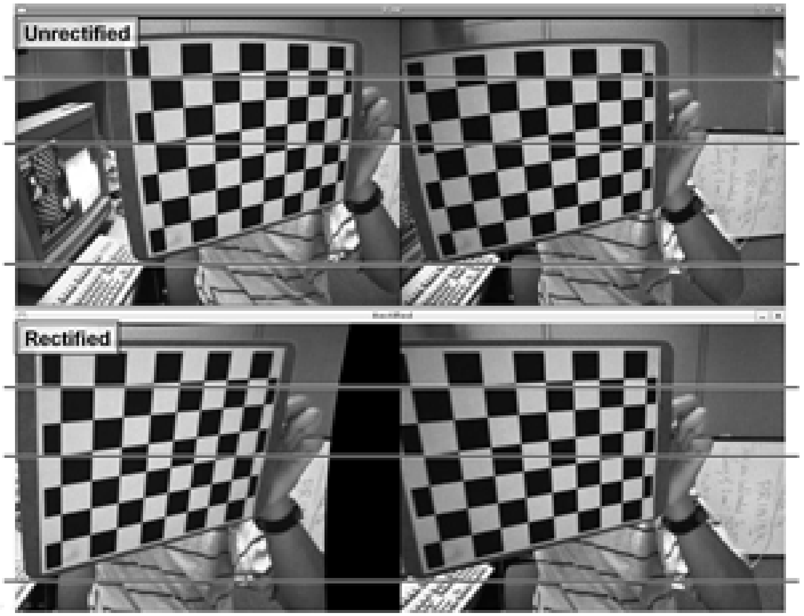
Un-distorted image

pr2_calibration

Stereo

- Once the left an right cameras are calibrated internally (intrinsics) and externally (extrinsics), we need to rectify the images



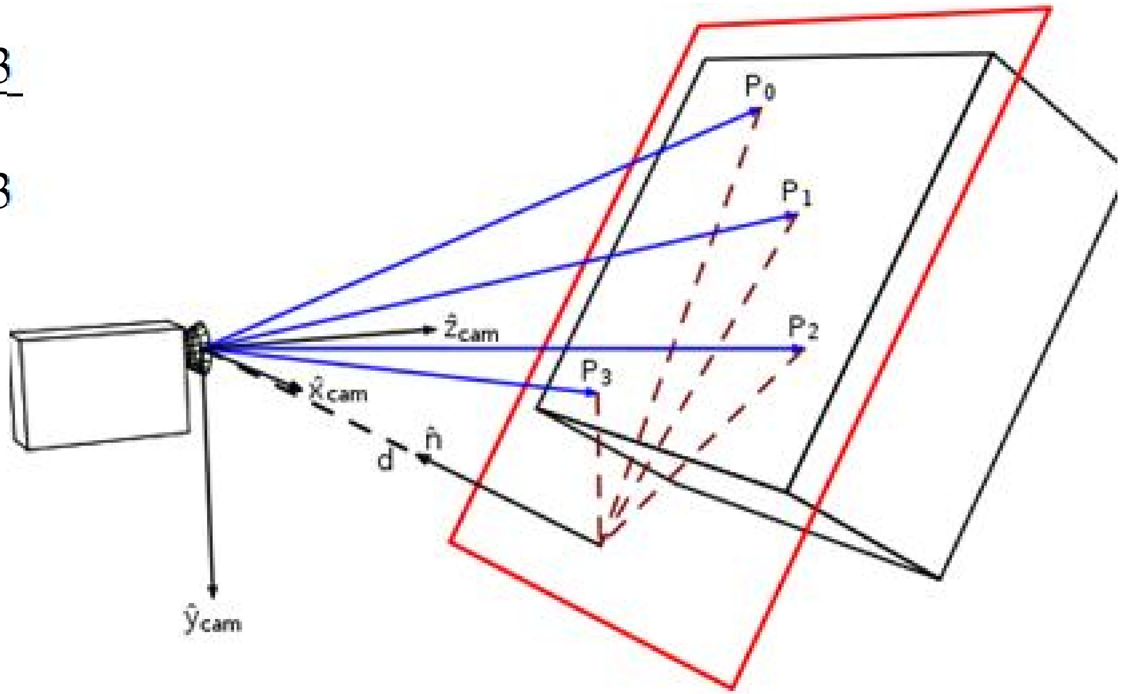


Homography

$$\tilde{u} = \frac{h_{11}u + h_{12}v + h_{13}}{h_{31}u + h_{32}v + h_{33}}$$

$$\tilde{v} = \frac{h_{21}u + h_{22}v + h_{23}}{h_{31}u + h_{32}v + h_{33}}$$

$$\begin{pmatrix} \tilde{u}w \\ \tilde{v}w \\ w \end{pmatrix} = H \begin{pmatrix} u \\ v \\ 1 \end{pmatrix}$$



Random Sample Consensus

- Do n iterations until #inliers > inlierThreshold
  - Draw k matches randomly
  - Find the transformation
  - Calculate inliers count
  - Remember the best solution

Problem: #matches, #inliers, k matches. How many iterations of RANSAC do you need to get the right answer?

The number of iterations required ~ $C * \left(\frac{\# matches}{\# inliers} \right)^k$

Machine Learning Library (MLL)

<u>CLASSIFICATION / REGRESSION</u>

(new) Fast Approximate NN (FLANN)

Naïve Bayes

CART

Random Forests

(new) Extremely Random Trees

(new) Gradient Boosting Trees

Statistical Boosting, 4 flavors

SVM

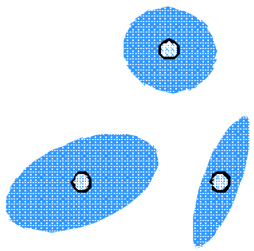
Face Detector

<u>CLUSTERING</u>

K-Means

EM

(Mahalanobis distance)



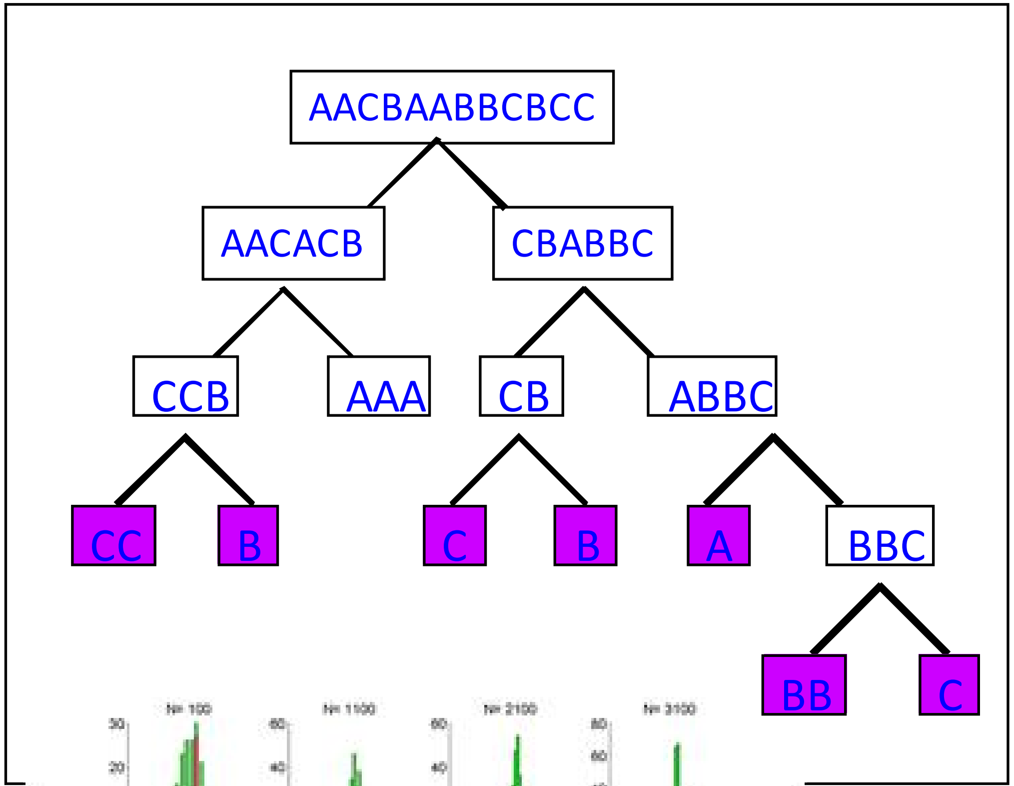
<u>TUNING/VALIDATION</u>

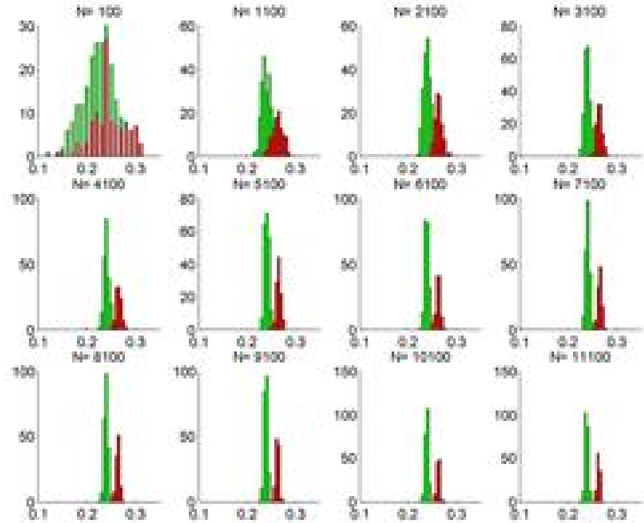
Cross validation

Bootstrapping

Variable importance

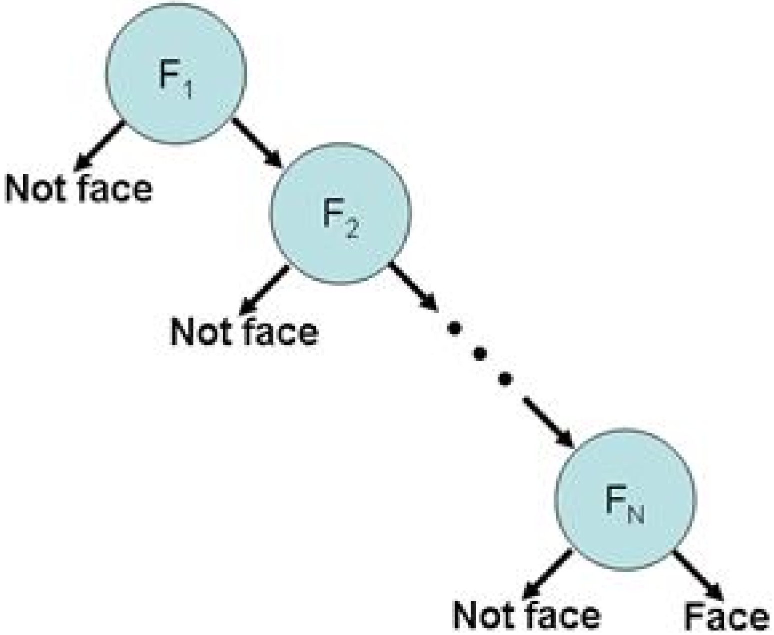
Sampling methods

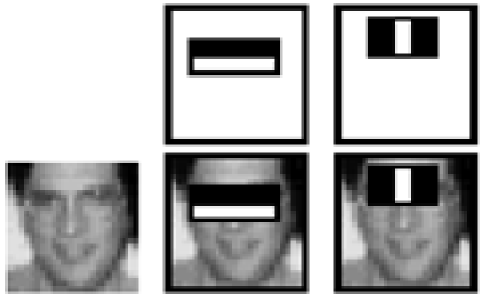




ML Lib Example:

Boosting: Face Detection with
Viola-Jones Rejection Cascade





In samples/cpp, see:
Multicascadeclassifier.cpp

Pedestrian Detection: HOG Descriptor

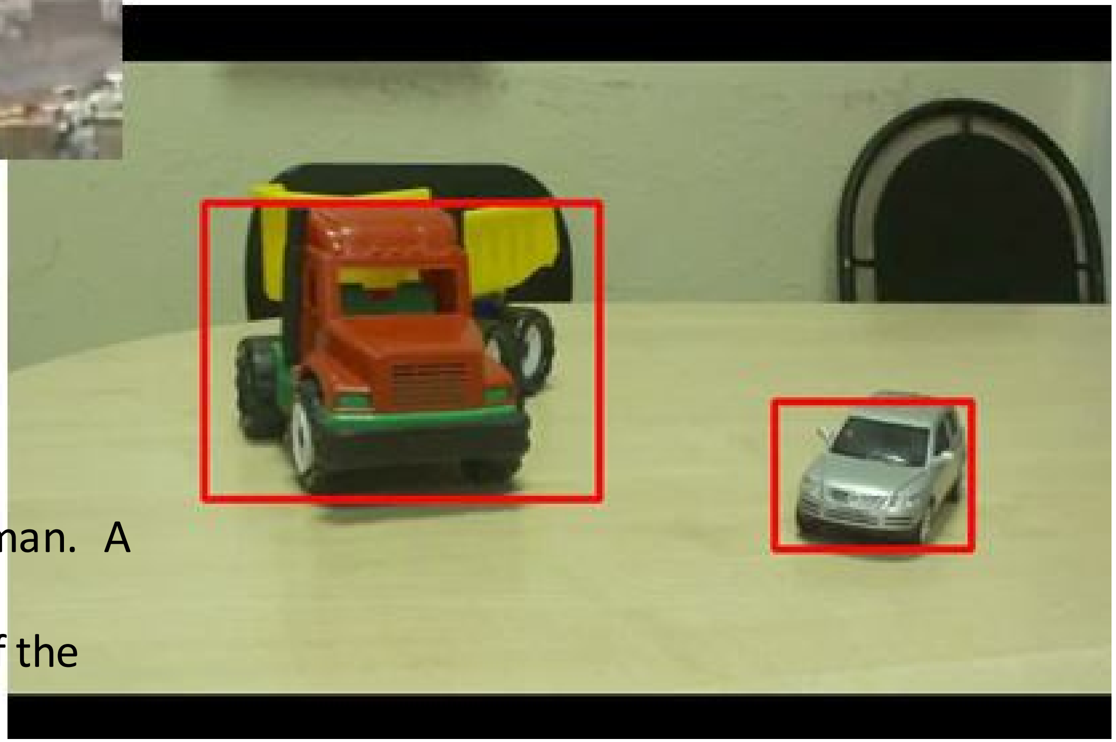
- Object shape is characterized by distributions of:
  - Gradient magnitude
  - Edge/Gradient orientation

- Grid of orientation histograms

Magnitude

Edge Orientation

Object detection

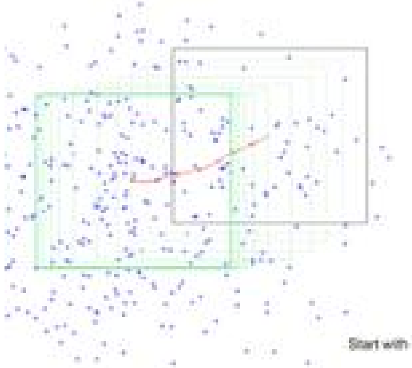


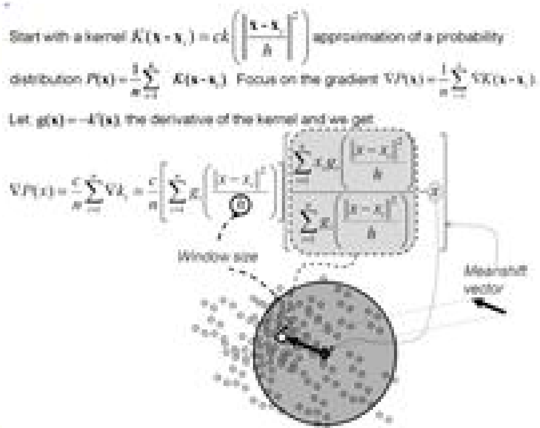
P. Felzenszwalb, D. McAllester, D. Ramaman. A Discriminatively Trained, Multiscale, Deformable Part Model. Proceedings of the IEEE CVPR 2008.

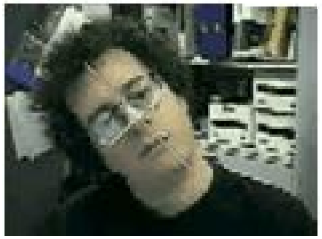
Tracking

2D

CamShift();
MeanShift();

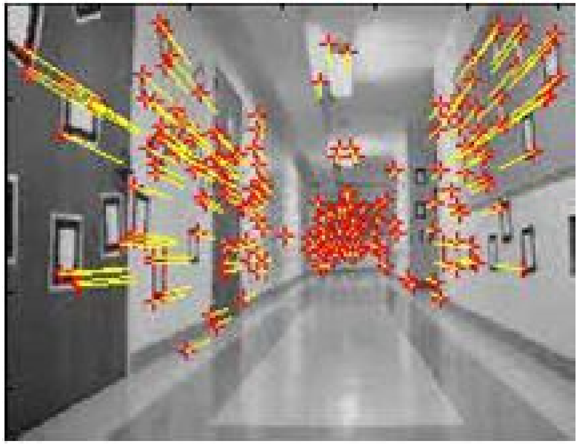






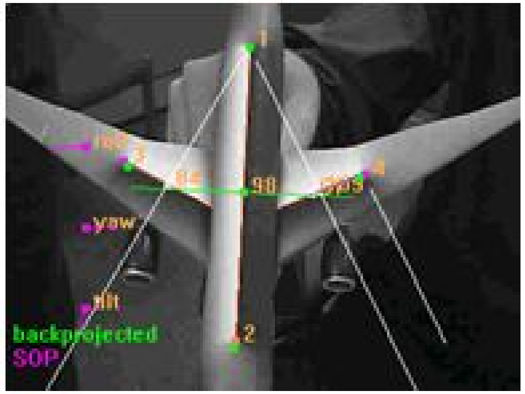
KalmanFilter::

calcOpticalFlowPyrLK()
Also see dense optical flow:
calcOpticalFlowFarneback()



3D

Posit();



Useful OpenCV Links

OpenCV Wiki:
http://opencv.willowgarage.com/wiki

User Group (~40K members):
http://tech.groups.yahoo.com/group/OpenCV/join

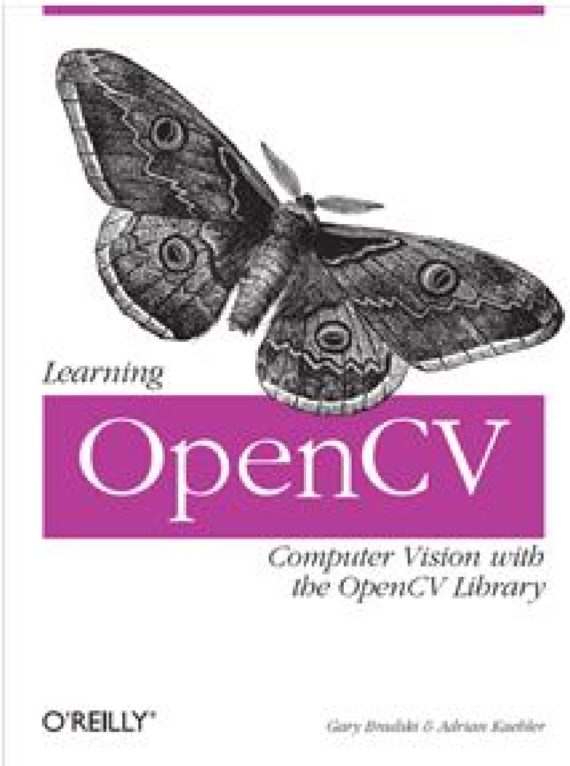
OpenCV Code Repository:
svn co https://code.ros.org/svn/opencv/trunk/opencv

New Book on OpenCV:
http://oreilly.com/catalog/9780596516130/

Or, direct from Amazon:
http://www.amazon.com/Learning-OpenCV-Computer-Vision-Library/dp/0596516134

Code examples from the book:
http://examples.oreilly.com/9780596516130/

Documentation
http://opencv.willowgarage.com/documentation/index.html



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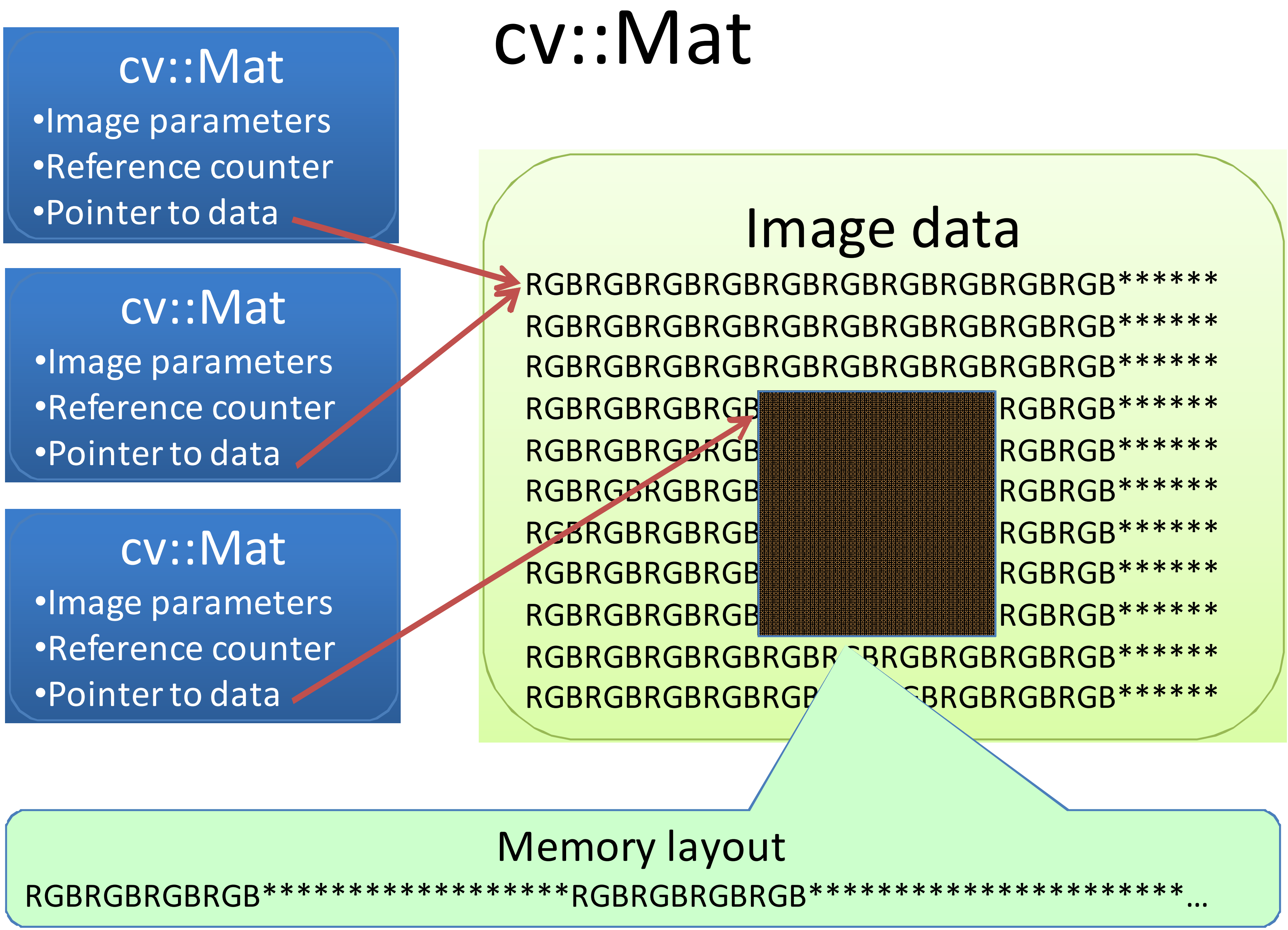
Main Structures

Key OpenCV Classes

`Point_`	Template 2D point class
`Point3_`	Template 3D point class
`Size_`	Template size (width, height) class
`Vec`	Template short vector class
`Scalar`	4-element vector
`Rect`	Rectangle
`Range`	Integer value range
`MatND`	Multi-dimensional dense array
`SparseMat`	Multi-dimensional sparse array
`Ptr`	Template smart pointer class


cv::Mat
cv::Mat
•Image parameters
•Reference counter
•Pointer to data
cv::Mat
•Image parameters
•Reference counter
•Pointer to data
cv::Mat
•Image parameters
•Reference counter
•Pointer to data
Image data
RGBRGBRGBRGBRGBRGBRGBRGBRGBRGB******
RGBRGBRGBRGBRGBRGBRGBRGBRGBRGB******
RGBRGBRGBRGBRGBRGBRGBRGBRGBRGB******
Memory layout
RGBRGBRGBRGB*****************RGBRGBRGBRGB**********************...

cv::Mat and std::vector

std::vector<Point3f>
XYZXYZXYZXYZXYZXYZXYZXYZXYZXYZXYZXYZXYZXYZ

A vector of n points

cv::Mat
- Image parameters
- Reference counter
- Pointer to data

cv::Mat
RGBRGBRGBRGBRGBRGBRGBRGBRGBRGBRGBRGBRGBRGB

Nx1 3-channel image

Mat are Simple

```
Mat M(480,640,CV_8UC3); // Make a 640x480 img
Rect roi(100,200, 20,40);    // Rectangle
Mat subM = M(roi);           // Take a sub region,
                             //  no copy is done

Mat_<Vec3b>::iterator it= subM.begin<Vec3b>(),
                    itEnd = subM.end<Vec3b>();
//Zero out pixels in subM where blue > red
for(; it != itEnd; ++it)
  if( (*it)[0] > (*it)[2]) (*it)[0] = 0;
```

Matrix Manipulation

`src.copyTo(dst)`	Copy matrix to another one
`src.convertTo(dst,type,scale,shift)`	Scale and convert to another datatype
`m.clone()`	Make deep copy of a matrix
`m.reshape(nch,nrows)`	Change matrix dimensions and/or number of channels without copying data
`m.row(i), m.col(i)`	Take a matrix row/column
`m.rowRange(Range(i1,i2))` `m.colRange(Range(j1,j2))`	Take a matrix row/column span
`m.diag(i)`	Take a matrix diagonal
`m(Range(i1,i2),Range(j1,j2)),` `m(roi)`	Take a submatrix
`m.repeat(ny,nx)`	Make a bigger matrix from a smaller one
`flip(src,dst,dir)`	Reverse the order of matrix rows and/or columns
`split(...)`	Split multi-channel matrix into separate channels
`merge(...)`	Make a multi-channel matrix out of the separate channels
`mixChannels(...)`	Generalized form of split() and merge()
`randShuffle(...)`	Randomly shuffle matrix elements

Example 1. Smooth image ROI in-place

```
Mat imgroi = image(Rect(10, 20, 100, 100));
GaussianBlur(imgroi, imgroi, Size(5, 5), 1.2, 1.2);
```

Example 2. Somewhere in a linear algebra algorithm

```
m.row(i) += m.row(j)*alpha;
```

Example 3. Copy image ROI to another image with conversion

```
Rect r(1, 1, 10, 20);
Mat dstroi = dst(Rect(0,10,r.width,r.height));
src(r).convertTo(dstroi, dstroi.type(), 1, 0);
```

Simple Matrix Operations

- `add()`, `subtract()`, `multiply()`, `divide()`, `absdiff()`, `bitwise_and()`, `bitwise_or()`, `bitwise_xor()`, `max()`, `min()`, `compare()`

– correspondingly, addition, subtraction, element-wise multiplication ... comparison of two matrices or a matrix and a scalar.

Example. Alpha compositing function:

```
void alphaCompose(const Mat& rgba1,
    const Mat& rgba2, Mat& rgba_dest)
{
    Mat a1(rgba1.size(), rgba1.type()), ra1;
    Mat a2(rgba2.size(), rgba2.type());
    int mixch[]={3, 0, 3, 1, 3, 2, 3, 3};
    mixChannels(&rgba1, 1, &a1, 1, mixch, 4);
    mixChannels(&rgba2, 1, &a2, 1, mixch, 4);
    subtract(Scalar::all(255), a1, ra1);
    bitwise_or(a1, Scalar(0,0,0,255), a1);
    bitwise_or(a2, Scalar(0,0,0,255), a2);
    multiply(a2, ra1, a2, 1./255);
    multiply(a1, rgba1, a1, 1./255);
    multiply(a2, rgba2, a2, 1./255);
    add(a1, a2, rgba_dest);
}
```

- `sum()`, `mean()`, `meanStdDev()`, `norm()`, `countNonZero()`, `minMaxLoc()`,

  – various statistics of matrix elements.

- `exp()`, `log()`, `pow()`, `sqrt()`, `cartToPolar()`, `polarToCart()`

  – the classical math functions.

- `scaleAdd()`, `transpose()`, `gemm()`, `invert()`, `solve()`, `determinant()`, `trace()` `eigen()`, `SVD`,

  – the algebraic functions + SVD class.

- `dft()`, `idft()`, `dct()`, `idct()`,

  – discrete Fourier and cosine transformations

For some operations a more convenient algebraic notation can be used, for example:

```
Mat delta = (J.t()*J + lambda*
    Mat::eye(J.cols, J.cols, J.type()))
    .inv(CV_SVD)*(J.t()*err);
```

implements the core of Levenberg-Marquardt optimization algorithm.

New C++ API: Usage Example

Focus Detector

C:

```
double calcGradients(const IplImage *src, int aperture_size = 7)
{
   CvSize sz = cvGetSize(src);
     IplImage* img16_x = cvCreateImage( sz, IPL_DEPTH_16S, 1);
     IplImage* img16_y = cvCreateImage( sz, IPL_DEPTH_16S, 1);

     cvSobel( src, img16_x, 1, 0, aperture_size);
     cvSobel( src, img16_y, 0, 1, aperture_size);

   IplImage* imgF_x = cvCreateImage( sz, IPL_DEPTH_32F, 1);
   IplImage* imgF_y = cvCreateImage( sz, IPL_DEPTH_32F, 1);

   cvScale(img16_x, imgF_x);
   cvScale(img16_y, imgF_y);

   IplImage* magnitude = cvCreateImage( sz, IPL_DEPTH_32F, 1);
   cvCartToPolar(imgF_x, imgF_y, magnitude);
   double res = cvSum(magnitude).val[0];

   cvReleaseImage( &magnitude );
   cvReleaseImage(&imgF_x);
     cvReleaseImage(&imgF_y);
     cvReleaseImage(&img16_x);
     cvReleaseImage(&img16_y);

   return res;
}
```

C++:

```
double contrast_measure(const Mat& img)
{
  Mat dx, dy;

  Sobel(img, dx, 1, 0, 3, CV_32F);
  Sobel(img, dy, 0, 1, 3, CV_32F);
  magnitude(dx, dy, dx);

  return sum(dx)[0];
}
```

Simple Image Processing

`filter2D()`	Non-separable linear filter
`sepFilter2D()`	Separable linear filter
`boxFilter()`, `GaussianBlur()`, `medianBlur()`, `bilateralFilter()`	Smooth the image with one of the linear or non-linear filters
`Sobel()`, `Scharr()`	Compute the spatial image derivatives
`Laplacian()`	compute Laplacian: $\Delta I = \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2}$
`erode()`, `dilate()`	Erode or dilate the image

Example. Filter image in-place with a 3x3 high-pass kernel (preserve negative responses by shifting the result by 128):

```
filter2D(image, image, image.depth(), (Mat_<float>(3,3)<<
   -1, -1, -1, -1, 9, -1, -1, -1, -1), Point(1,1), 128);
```

Image Conversions

`resize()`	Resize image
`getRectSubPix()`	Extract an image patch
`warpAffine()`	Warp image affinely
`warpPerspective()`	Warp image perspectively
`remap()`	Generic image warping
`convertMaps()`	Optimize maps for a faster remap() execution

Example. Decimate image by factor of $\sqrt{2}$:

```
Mat dst; resize(src, dst, Size(), 1./sqrt(2), 1./sqrt(2))
```

`cvtColor()`	Convert image from one color space to another
`threshold()`, `adaptivethreshold()`	Convert grayscale image to binary image using a fixed or a variable threshold
`floodFill()`	Find a connected component using region growing algorithm
`integral()`	Compute integral image
`distanceTransform()`	build distance map or discrete Voronoi diagram for a binary image.
`watershed()`, `grabCut()`	marker-based image segmentation algorithms. See the samples `watershed.cpp` and `grabcut.cpp`.

Histogram

Histograms

calcHist()	Compute image(s) histogram
calcBackProject()	Back-project the histogram
equalizeHist()	Normalize image brightness and contrast
compareHist()	Compare two histograms

Example. Compute Hue-Saturation histogram of an image:

```
Mat hsv, H; MatND tempH;
cvtColor(image, hsv, CV_BGR2HSV);
int planes[]={0, 1}, hsize[] = {32, 32};
calcHist(&hsv, 1, planes, Mat(), tempH, 2, hsize, 0);
H = tempH;
```

I/O

Writing and reading raster images

```
imwriteimwrite("myimage.jpg", image);
Mat image_color_copy = imread("myimage.jpg", 1);
Mat image_grayscale_copy = imread("myimage.jpg", 0);
```

The functions can read/write images in the following formats: ***BMP (.bmp), JPEG (.jpg, .jpeg), TIFF (.tif, .tiff), PNG (.png), PBM/PGM/PPM (.p?m), Sun Raster (.sr), JPEG 2000 (.jp2).*** *Every format supports 8-bit, 1- or 3-channel images. Some formats (PNG, JPEG 2000) support 16 bits per channel.*

Reading video from a file or from a camera

```
VideoCapture cap;
if(argc > 1) cap.open(string(argv[1])); else cap.open(0);
Mat frame; namedWindow("video", 1);
for(;;) {
   cap >> frame; if(!frame.data) break;
   imshow("video", frame); if(waitKey(30) >= 0) break;
}
```

Serialization I/O

Data I/O

XML/YAML storages are collections (possibly nested) of scalar values, structures and heterogeneous lists.

Writing data to YAML (or XML)

```
// Type of the file is determined from the extension
   FileStorage fs("test.yml", FileStorage::WRITE);
   fs << "i" << 5 << "r" << 3.1 << "str" << "ABCDEFGH";
   fs << "mtx" << Mat::eye(3,3,CV_32F);
   fs << "mylist" << "[" << CV_PI << "1+1" <<
      "{:" << "month" << 12 << "day" << 31 << "year"
      << 1969 << "}" << "]";
   fs << "mystruct" << "{" << "x" << 1 << "y" << 2 <<
      "width" << 100 << "height" << 200 << "lbp" << "[:";
   const uchar arr[] = {0, 1, 1, 0, 1, 1, 0, 1};
   fs.writeRaw("u", arr, (int)(sizeof(arr)/sizeof(arr[0])));
   fs << "]" << "}";
```

Scalars (integers, floating-point numbers, text strings), matrices, STL vectors of scalars and some other types can be written to the file storages using << operator

Serialization I/O

Reading the data back

```
// Type of the file is determined from the content
FileStorage fs("test.yml", FileStorage::READ);
int i1 = (int)fs["i"]; double r1 = (double)fs["r"];
string str1 = (string)fs["str"];
Mat M; fs["mtx"] >> M;
FileNode tl = fs["mylist"];
CV_Assert(tl.type() == FileNode::SEQ && tl.size() == 3);
double tl0 = (double)tl[0]; string tl1 = (string)tl[1];
int m = (int)tl[2]["month"], d = (int)tl[2]["day"];
int year = (int)tl[2]["year"];
FileNode tm = fs["mystruct"];
Rect r; r.x = (int)tm["x"], r.y = (int)tm["y"];
r.width = (int)tm["width"], r.height = (int)tm["height"];
int lbp_val = 0;
FileNodeIterator it = tm["lbp"].begin();
for(int k = 0; k < 8; k++, ++it)
   lbp_val |= ((int)*it) << k;
```

Scalars are read using the corresponding FileNode's cast operators. Matrices and some other types are read using >> operator. Lists can be read using FileNodeIterator's.

GUI ("HighGUI")

`namedWindow(winname,flags)`	Create named highgui window
`destroyWindow(winname)`	Destroy the specified window
`imshow(winname, mtx)`	Show image in the window
`waitKey(delay)`	Wait for a key press during the specified time interval (or forever). Process events while waiting. *Do not forget to call this function several times a second in your code.*
`createTrackbar(...)`	Add trackbar (slider) to the specified window
`setMouseCallback(...)`	Set the callback on mouse clicks and movements in the specified window

See `camshiftdemo.c` and other OpenCV samples on how to use the GUI functions.

Camera Calibration, Pose, Stereo

calibrateCamera()	Calibrate camera from several views of a calibration pattern.
findChessboardCorners()	Find feature points on the checker-board calibration pattern.
solvePnP()	Find the object pose from the known projections of its feature points.
stereoCalibrate()	Calibrate stereo camera.
stereoRectify()	Compute the rectification transforms for a calibrated stereo camera.
initUndistortRectifyMap()	Compute rectification map (for remap()) for each stereo camera head.
StereoBM, StereoSGBM	The stereo correspondence engines to be run on rectified stereo pairs.
reprojectImageTo3D()	Convert disparity map to 3D point cloud.
findHomography()	Find best-fit perspective transformation between two 2D point sets.

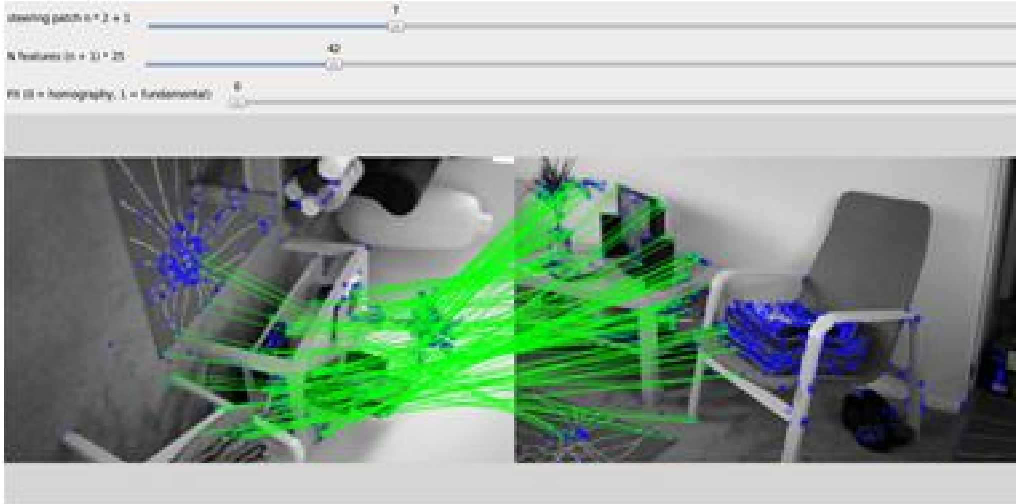
To calibrate a camera, you can use calibration.cpp or stereo_calib.cpp samples. To get the disparity maps and the point clouds, use stereo_match.cpp sample.

Problem: planar object detection

Features 2D

Read two input images:

```
Mat img1 = imread(argv[1], CV_LOAD_IMAGE_GRAYSCALE);
```



Detect keypoints in both images:

```
// detecting keypoints
FastFeatureDetector detector(15);
vector<KeyPoint> keypoints1;
detector.detect(img1, keypoints1);
```

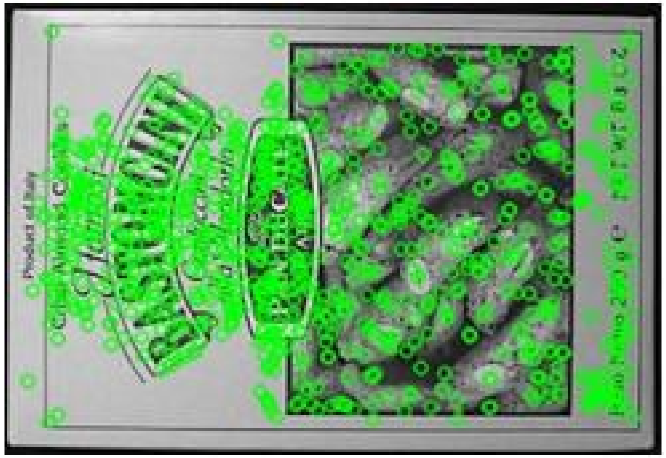
Compute descriptors for each of the keypoints:

```
// computing descriptors
SurfDescriptorExtractor extractor;
Mat descriptors1;
extractor.compute(img1, keypoints1, descriptors1);
```

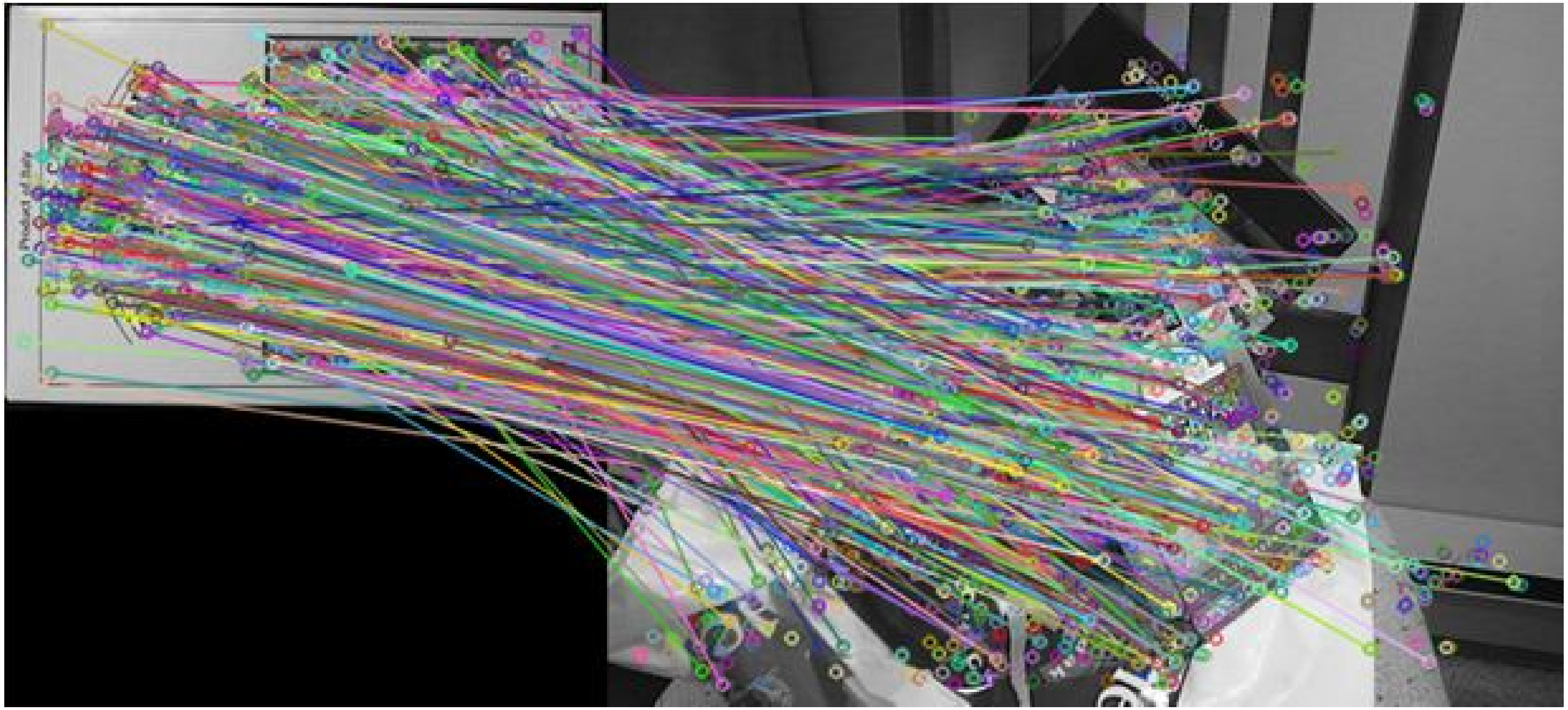
Now, find the closest matches between descriptors from the first image to the second:

```
// matching descriptors
BruteForceMatcher<L2<float> > matcher;
vector<DMatch> matches;
matcher.match(descriptors1, descriptors2, matches);
```

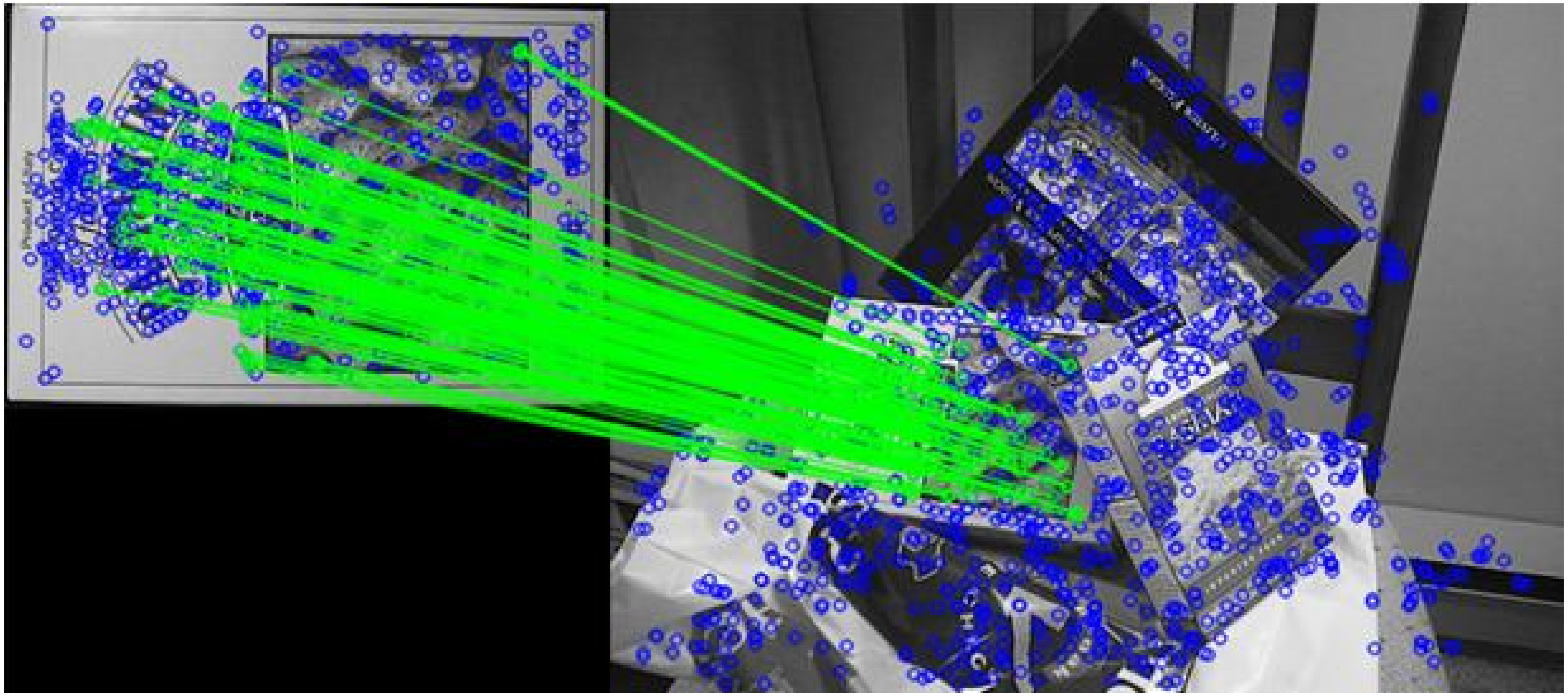
Keypoints example



Matching descriptors example



Geometry validation



Object Recognition

`matchTemplate`	Compute proximity map for given template.
`CascadeClassifier`	Viola's Cascade of Boosted classifiers using Haar or LBP features. Suits for detecting faces, facial features and some other objects without diverse textures. See `facedetect.cpp`
`HOGDescriptor`	N. Dalal's object detector using Histogram-of-Oriented-Gradients (HOG) features. Suits for detecting people, cars and other objects with well-defined silhouettes. See `peopledetect.cpp`

Python Face Detector Node: 1

The Setup

```
#!/usr/bin/python
"""
This program is demonstration python ROS Node for face and object detection using haar-like features.
The program finds faces in a camera image or video stream and displays a red box around them. Python implementation by:
Roman Stanchak, James Bowman
"""
import roslib
roslib.load_manifest('opencv_tests')
import sys
import os
from optparse import OptionParser
import rospy
import sensor_msgs.msg
from cv_bridge import CvBridge
import cv

# Parameters for haar detection
# From the API:
# The default parameters (scale_factor=2, min_neighbors=3, flags=0) are tuned
# for accurate yet slow object detection. For a faster operation on real video
# images the settings are:
# scale_factor=1.2, min_neighbors=2, flags=CV_HAAR_DO_CANNY_PRUNING,
# min_size=<minimum possible face size

min_size = (20, 20)
image_scale = 2
haar_scale = 1.2
min_neighbors = 2
haar_flags = 0
```

Python Face Detector Node: 2

The Core

```
if __name__ == '__main__':

  pkgdir = roslib.packages.get_pkg_dir("opencv2")
  haarfile = os.path.join(pkgdir, "opencv/share/opencv/haarcascades/haarcascade_frontalface_alt.xml")

  parser = OptionParser(usage = "usage: %prog [options] [filename|camera_index]")
  parser.add_option("-c", "--cascade", action="store", dest="cascade", type="str", help="Haar cascade file, default %default", default = haarfile)
  (options, args) = parser.parse_args()

  cascade = cv.Load(options.cascade)
  br = CvBridge()

  def detect_and_draw(imgmsg):
    img = br.imgmsg_to_cv(imgmsg, "bgr8")
    # allocate temporary images
    gray = cv.CreateImage((img.width,img.height), 8, 1)
    small_img = cv.CreateImage((cv.Round(img.width / image_scale),
               cv.Round (img.height / image_scale)), 8, 1)

    # convert color input image to grayscale
    cv.CvtColor(img, gray, cv.CV_BGR2GRAY)

    # scale input image for faster processing
    cv.Resize(gray, small_img, cv.CV_INTER_LINEAR)

    cv.EqualizeHist(small_img, small_img)

    if(cascade):
      faces = cv.HaarDetectObjects(small_img, cascade, cv.CreateMemStorage(0),
                   haar_scale, min_neighbors, haar_flags, min_size)
      if faces:
        for ((x, y, w, h), n) in faces:
          # the input to cv.HaarDetectObjects was resized, so scale the
          # bounding box of each face and convert it to two CvPoints
          pt1 = (int(x * image_scale), int(y * image_scale))
          pt2 = (int((x + w) * image_scale), int((y + h) * image_scale))
          cv.Rectangle(img, pt1, pt2, cv.RGB(255, 0, 0), 3, 8, 0)

    cv.ShowImage("result", img)
    cv.WaitKey(6)

  rospy.init_node('rosfacedetect')
  image_topic = rospy.resolve_name("image")
  rospy.Subscriber(image_topic, sensor_msgs.msg.Image, detect_and_draw)
  rospy.spin()
```

Outline

- OpenCV Overview
- Functionality
- Programming with OpenCV
- OpenCV on CPU & GPU
- Mobile vision

Hardware optimization: Intel architectures

- Technologies
  - SSE
  - TBB
  - IPP
- Highlights of C++ in-house optimization
  - arithmetical operations on large matrices/images: add, sub, absdiff - **5-6x faster**
  - image filtering: e.g. median 3x3 filter is **20x faster**!
  - geometrical transformations: resize is **2.5 faster**
  - template matching: **2-2.5 faster**
  - large matrix processing: SVD of 50x50-1000x1000 matrices is **1.4-2.7x faster**

OpenCV GPU Module

Goals:

- Provide developers with a convenient computer vision framework on the GPU
- Maintain conceptual consistency with the current CPU functionality
- Achieve the best performance with GPUs
  - Efficient kernels tuned for modern architectures
  - Optimized dataflows (asynchronous execution, copy overlaps, zero-copy)

OpenCV GPU Module Contents

- Image processing building blocks:

Color conversions

Geometrical transforms

Per-element operations

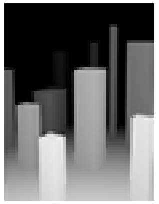
Integrals, reductions

Template matching

Filtering engine

Feature detectors

- High-level algorithms:

Stereo matching 

Face detection 

Feature matching 

OpenCV GPU Module Usage

- Prerequisites:
  - Get sources from SourceForge or SVN
  - CMake
  - NVIDIA Display Driver
  - NVIDIA GPU Computing Toolkit (for CUDA)
- Build OpenCV with CUDA support
- **`#include <opencv2/gpu/gpu.hpp>`**

http://opencv.willowgarage.com/wiki/InstallGuide

OpenCV GPU Data Structures

- Class GpuMat
  - For storing 2D image in GPU memory, just like class cv::Mat
  - Reference counting
  - Can point to data allocated by user
- Class CudaMem
  - For pinned memory support
  - Can be transformed into cv::Mat or cv::gpu::GpuMat
- Class Stream
  - Overloads with extra Stream parameter

```
// class GpuMat
GpuMat(Size size, int type);
GpuMat(const GpuMat& m);
explicit GpuMat (const Mat& m);
GpuMat& operator = (const GpuMat& m);
GpuMat& operator = (const Mat& m);
void upload(const Mat& m);
void upload(const CudaMem& m, Stream&
stream);
void download(Mat& m) const;
void download(CudaMem& m, Stream& stream)
const;
```

```
// class Stream
bool queryIfComplete();
void waitForCompletion();
void enqueueDownload(const GpuMat& src,
Mat& dst);
void enqueueUpload(const Mat& src,
GpuMat& dst);
void enqueueCopy(const GpuMat& src,
GpuMat& dst);
```

OpenCV GPU Module Example

```
Mat frame;
VideoCapture capture(camera);
cv::HOGDescriptor hog;

hog.setSVMDetector(cv::HOGDescriptor
::
getDefaultPeopleDetectorector());

capture >> frame;



vector<Rect> found;
hog.detectMultiScale(frame, found,
    1.4,  Size(8, 8), Size(0, 0),
1.05, 8);
```

```
Mat frame;
VideoCapture capture(camera);
cv::gpu::HOGDescriptor hog;

hog.setSVMDetector(cv::HOGDescriptor
::
getDefaultPeopleDetectorector());

capture >> frame;

GpuMat gpu_frame;
gpu_frame.upload(frame);

vector<Rect> found;
hog.detectMultiScale(gpu_frame,
found,
    1.4, Size(8, 8), Size(0, 0),
1.05, 8);
```

- Designed very similar!

OpenCV and NPP

- NPP is NVIDIA Performance Primitives library of signal and image processing functions (similar to Intel IPP)
  - NVIDIA will continue adding new primitives and optimizing for future architectures

- GPU module uses NPP whenever possible
  - Highly optimized implementations for all supported NVIDIA architectures and OS
  - Part of CUDA Toolkit – no additional dependencies

- OpenCV extends NPP and uses it to build higher level CV

OpenCV GPU Module Performance

Tesla C2050 (Fermi) vs. Core i5-760 2.8GHz (4 cores, TBB, SSE)

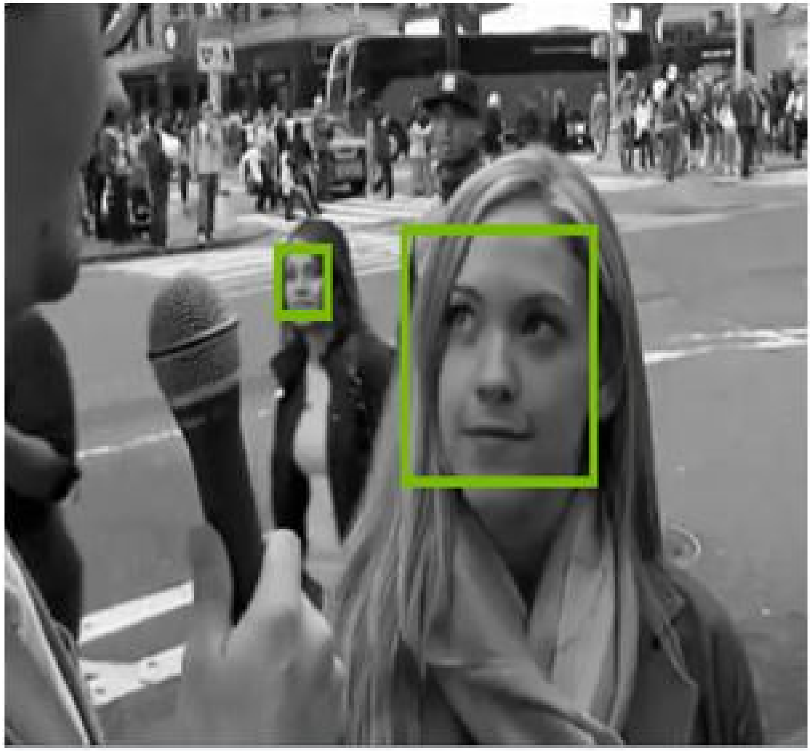
- Average speedup for primitives: 33×
  - For "good" data (large images are better)
  - Without copying to GPU

What can you get from your computer?

- opencv\samples\gpu\perfomance

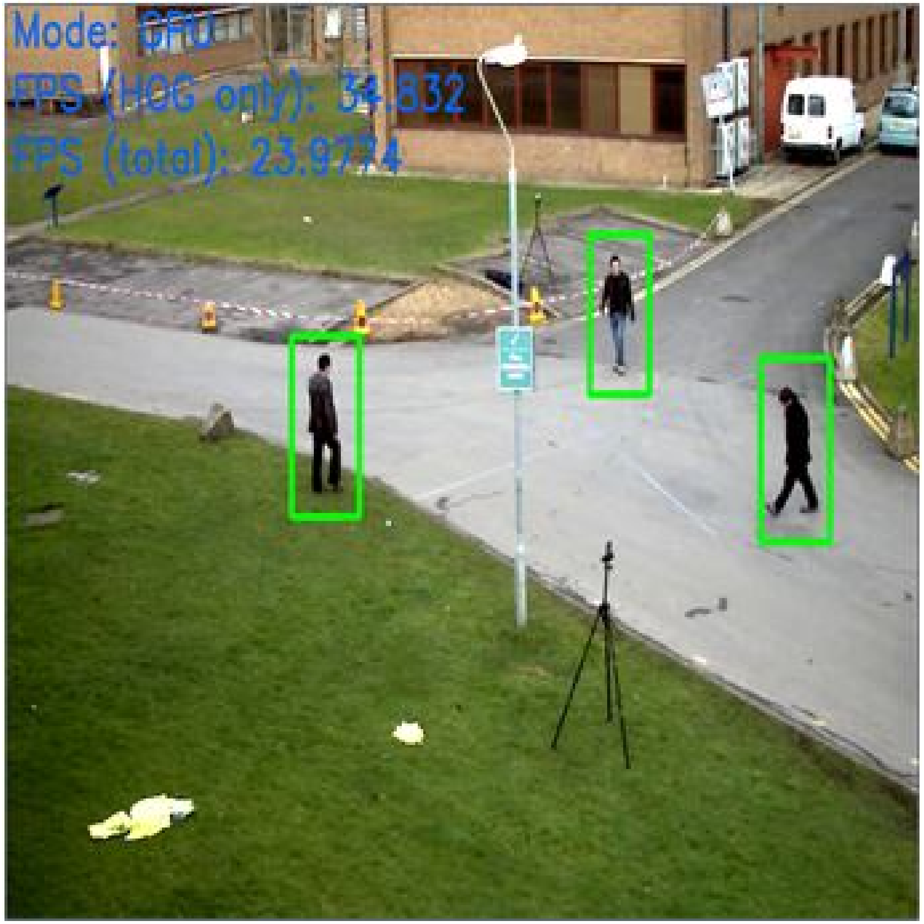
OpenCV GPU: Viola-Jones Cascade Classifier

- Used for face detection
- Speed-up ~ **6×**
- Based on NCV classes (NVIDIA implementation)



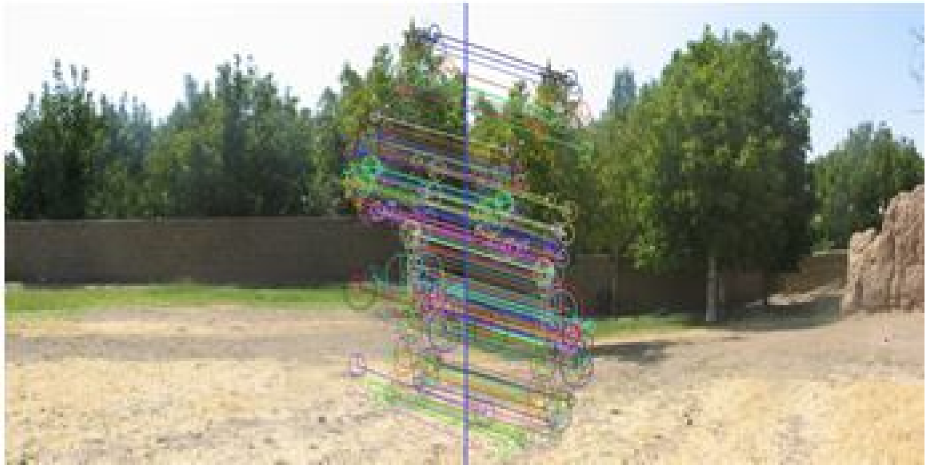
OpenCV GPU: Histogram of Oriented Gradients

- Used for pedestrian detection
- Speed-up ~ **8×**



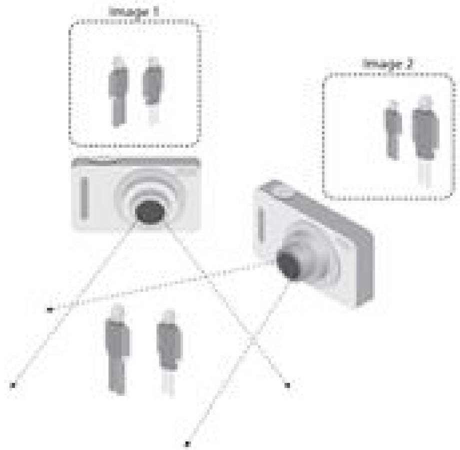
OpenCV GPU: Speeded Up Robust Features

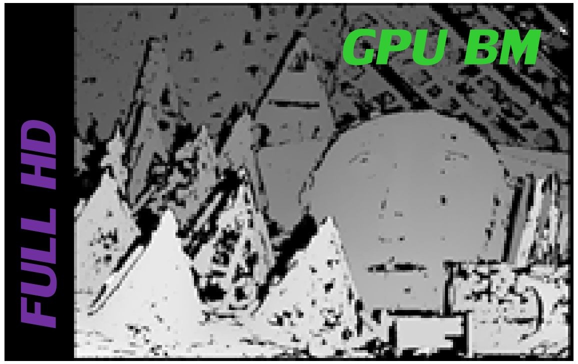
- SURF (**12×**)
- Bruteforce matcher
  - K-Nearest search (**20-30×**)
  - In radius search (**3-5×**)

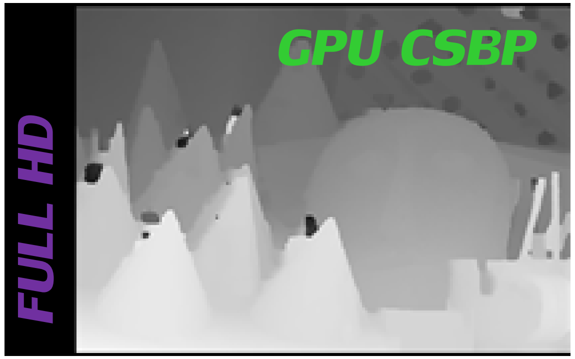


OpenCV GPU: Stereo Vision

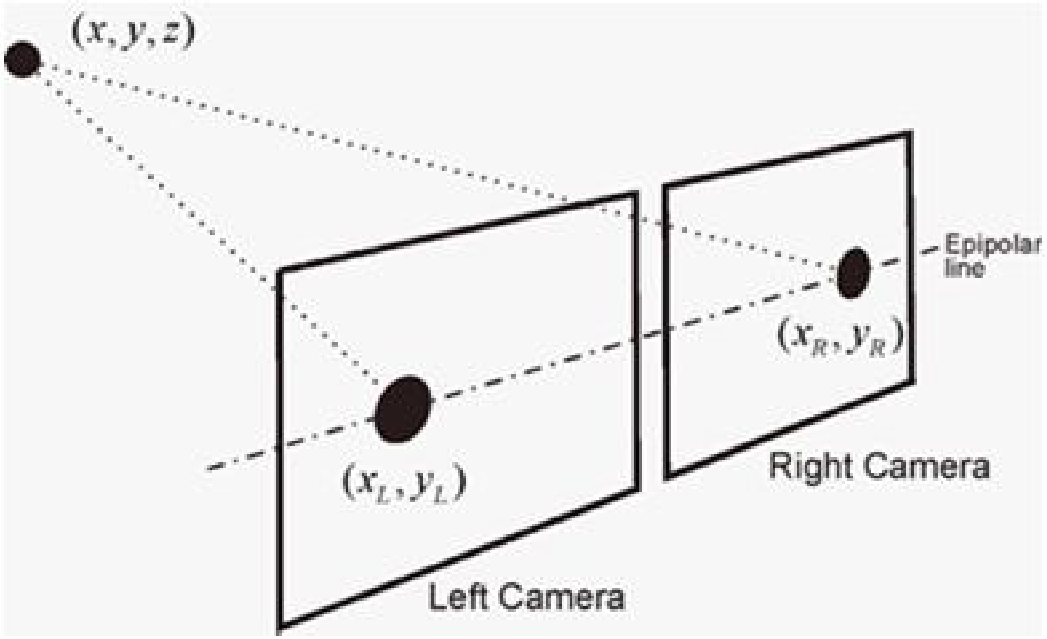
- Stereo Block Matching (**7×**)
  - Can run Full HD real-time on Dual-GPU
- Hierarchical Dense Stereo
  - Belief Propagation (**20×**)
  - Constant space BP (**50-100×**)







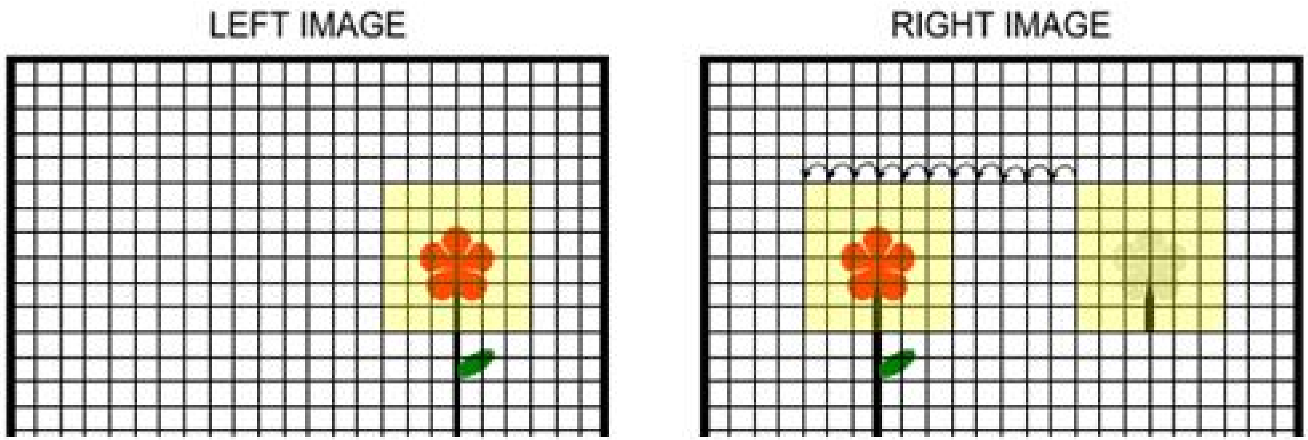
Epipolar geometry



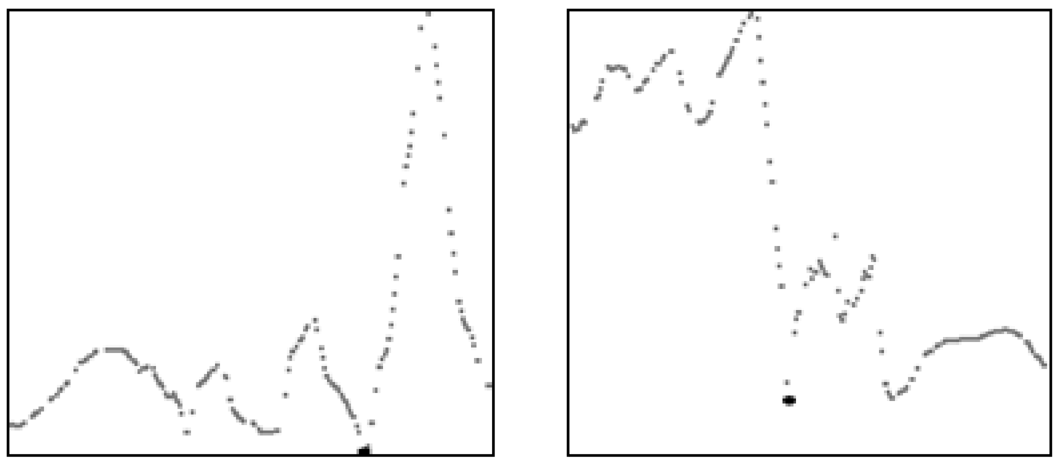
Fundamental matrix constraint

$$(x_L, y_L, 1) \cdot F \cdot \begin{pmatrix} x_R \\ y_R \\ 1 \end{pmatrix} = 0$$

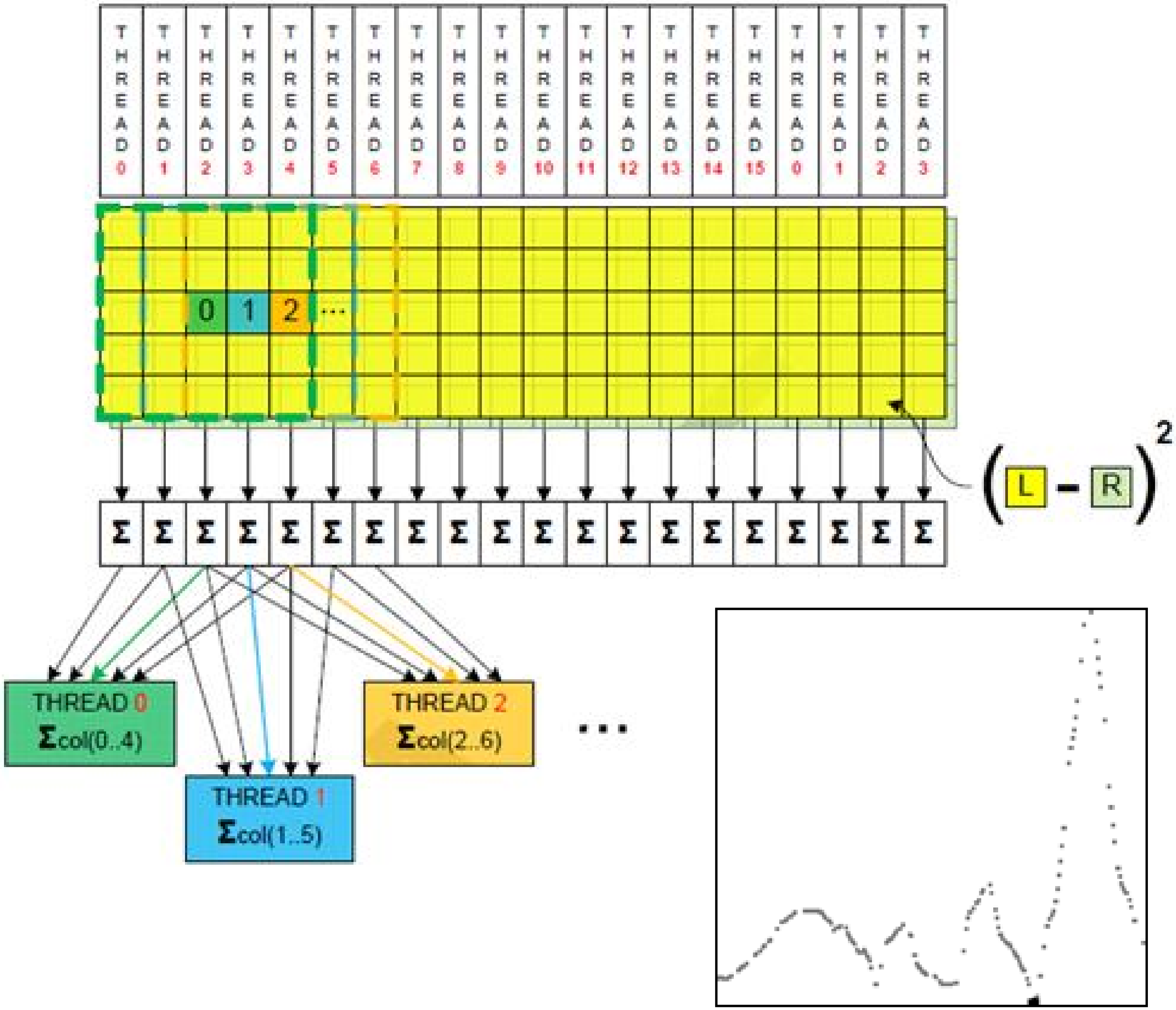
Block matching



$$SSD_{x,y} = \sum_{i=x-R_H}^{x+R_H} \sum_{j=y-R_V}^{y+R_V} \left(Left_{i,j} - Right_{i-d,j}\right)^2$$



Parallel algorithm



Оптимизация кода на CUDA

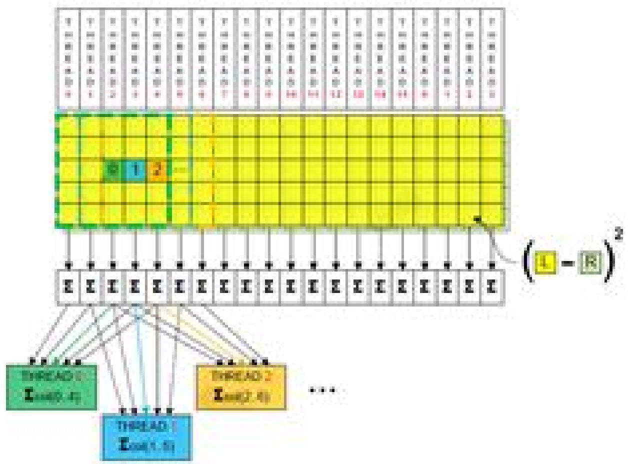
Проблема №1: occupancy

- Дефицит регистров
  - Отказ от текстурного механизма
  - Ручная оптимизация кода на CUDA
- Дефицит SMEM
  - Использование unsigned char и short
  - Подбор размера блока потоков

Оптимизация кода на CUDA

Проблема №3: сложные вычисления

- Переход к относительной адресации памяти внутри потоков
- Переход на быстрые операции
- Удаление повторных вычислений



Stereo on HD in realtime

Outline

- OpenCV Overview
- Functionality
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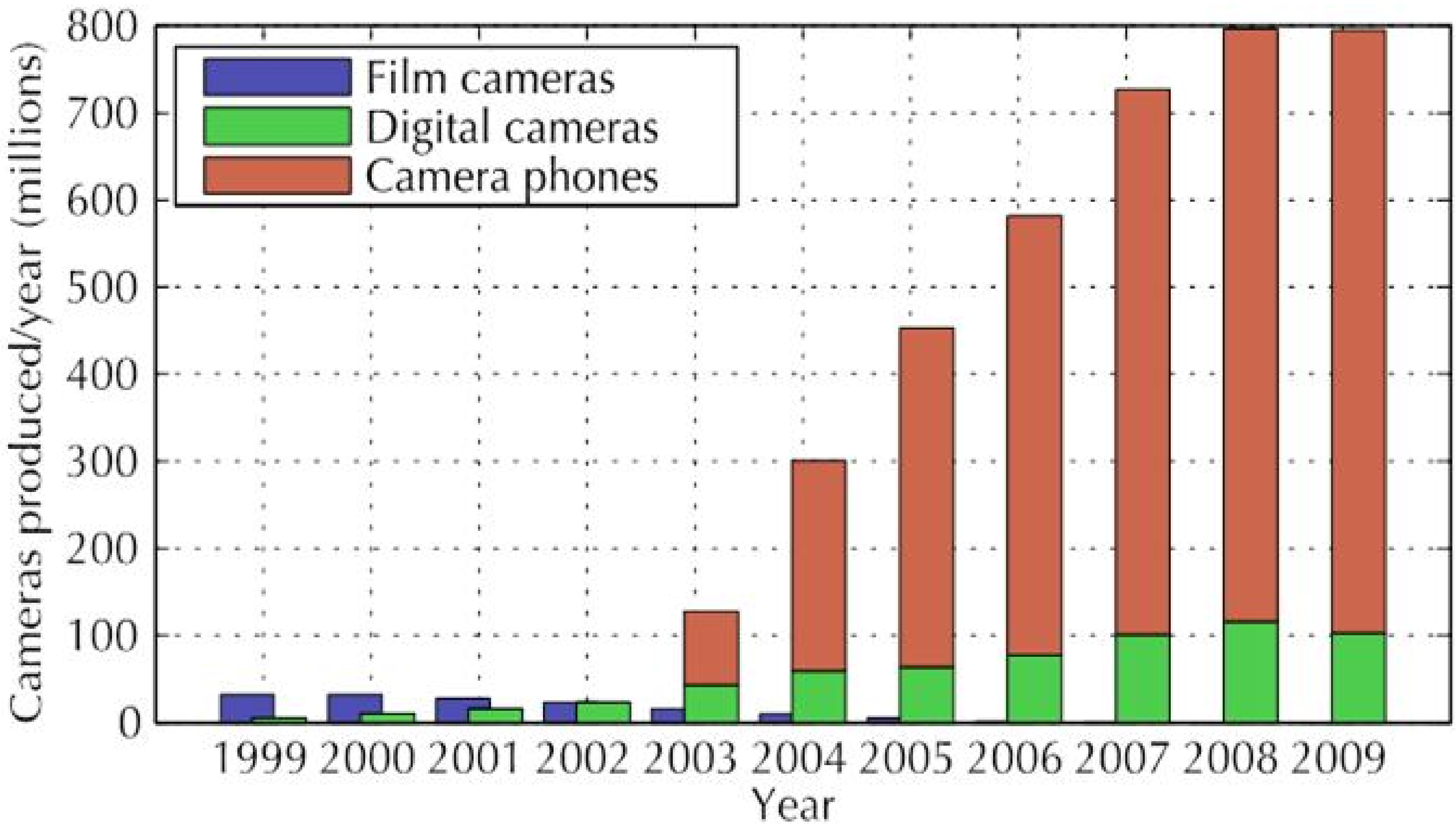
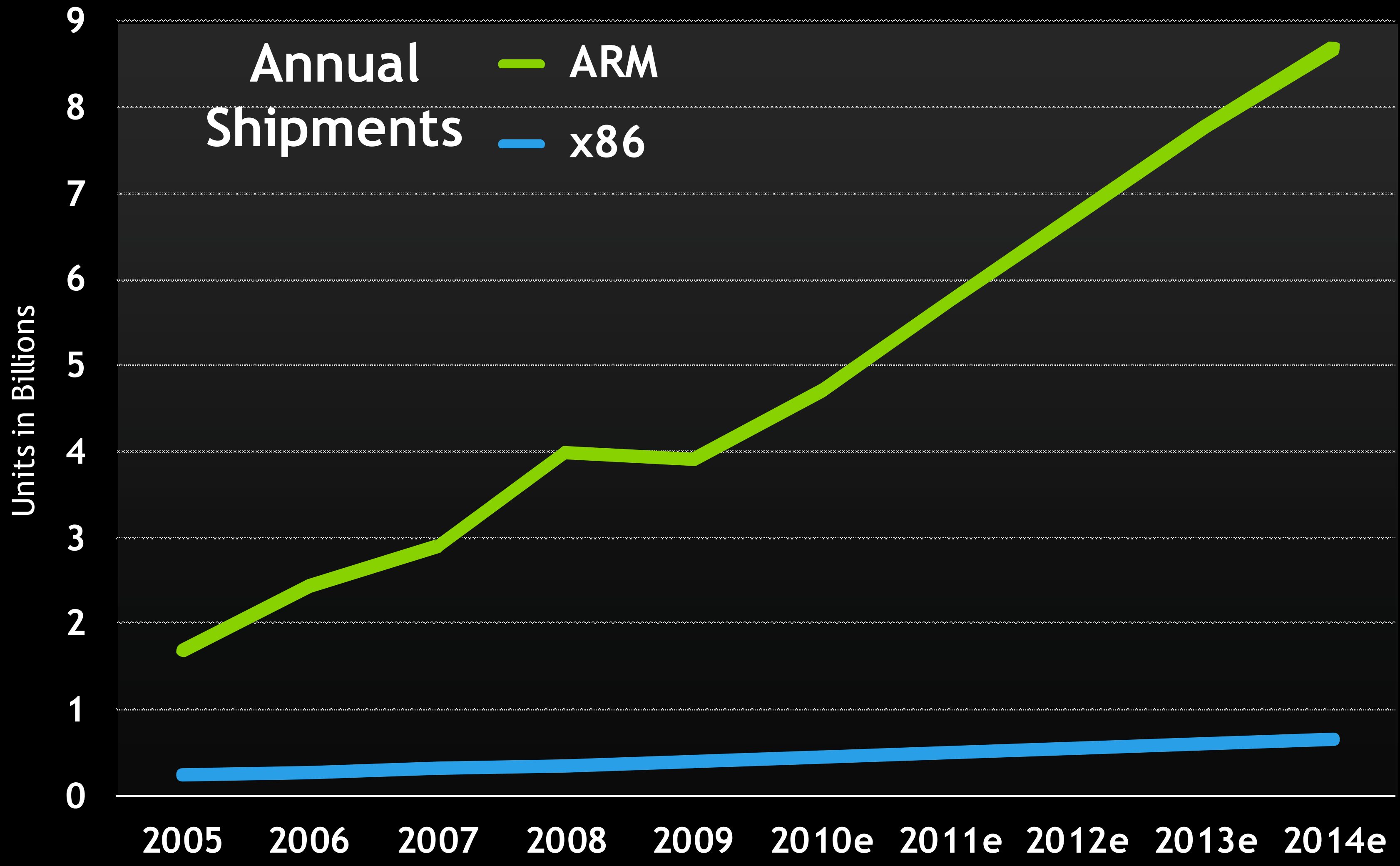
- OpenCV on GPU
- Mobile vision

Traditional cameras vs. camera phones



ARM is Pervasive and Open



Source: ARM, Mercury Research, NVIDIA

Using OpenCV for Android

- **OpenCV 2.3 for Android:**
  - **Native Android Camera Support**
  - **Multithreading**
  - **Java API (soon)**
  - **Tegra HW Optimizations (soon)**

Wiki with the latest information:

http://opencv.willowgarage.com/wiki/Android

Support/discussion

group:::https://groups.google.com/group/android-opencv

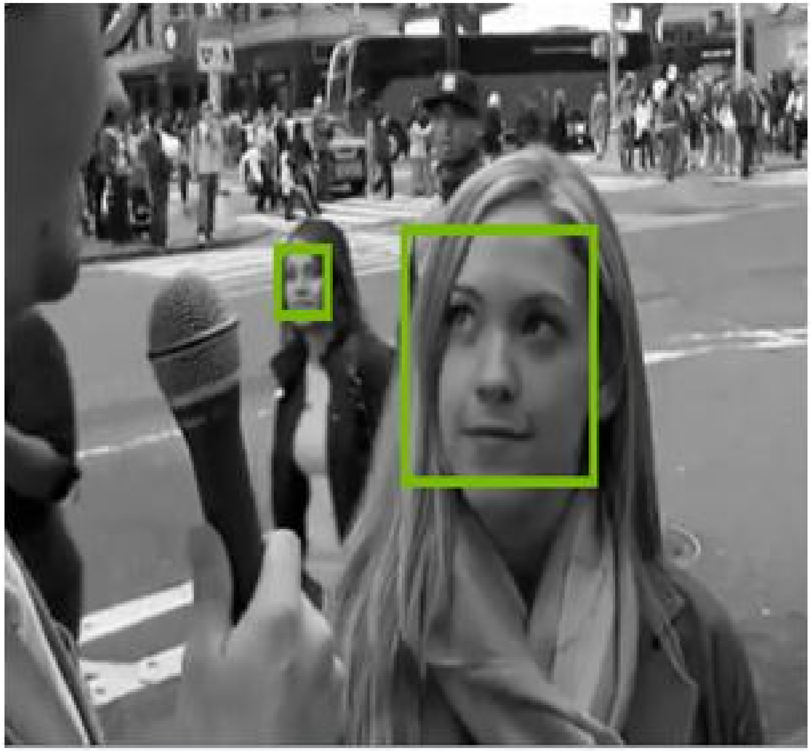
Practical session

- Look for opencv_practical_session.tar.gz on your USB stick
- Unzip and install OpenCV
- Make sure you have your favorite compiler environment ready
- CMake is optional but highly recommended

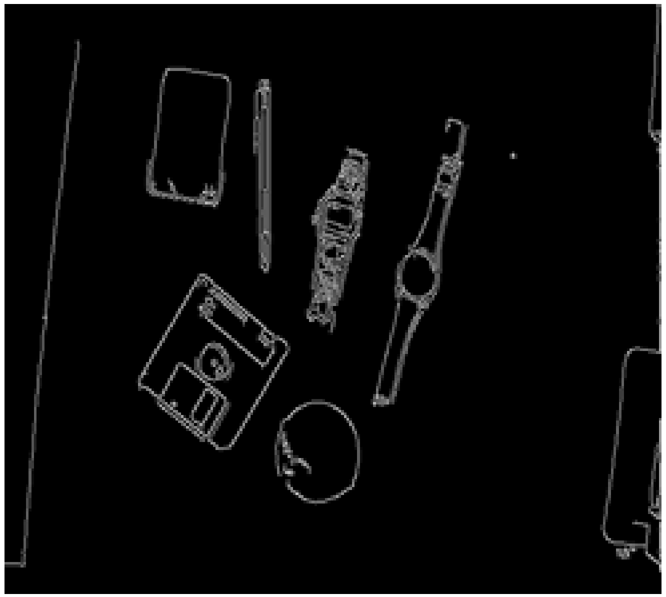
QUESTIONS?

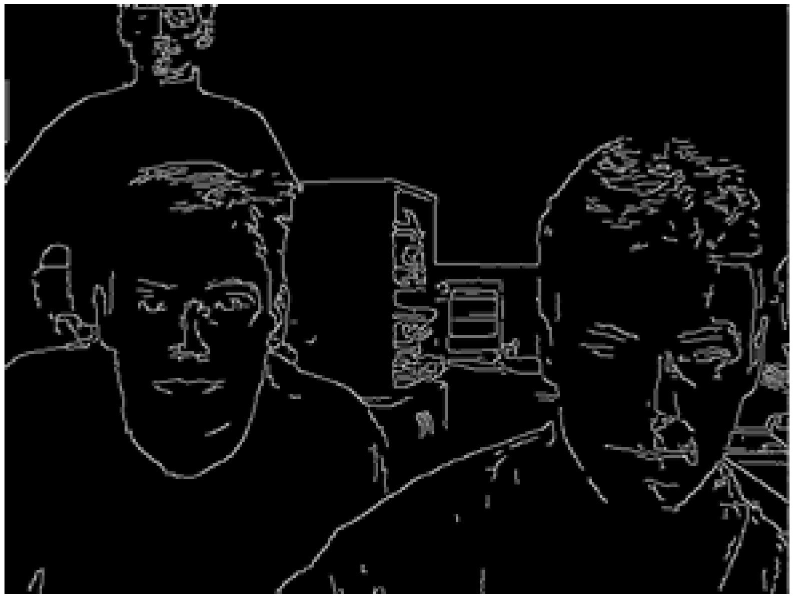
OpenCV GPU: Viola-Jones Cascade Classifier

- Used for face detection
- Speed-up ~ **6×**
- Based on NCV classes (NVIDIA implementation)



Canny Edge Detector

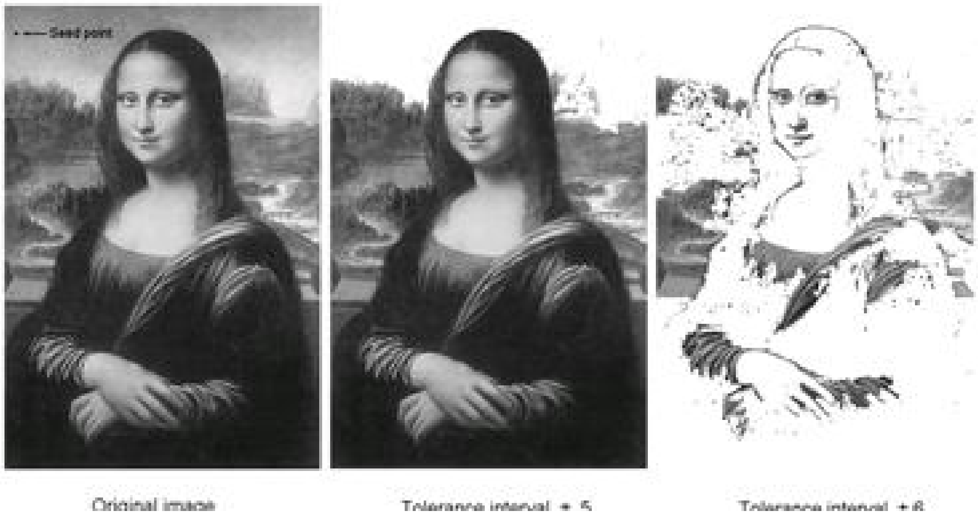




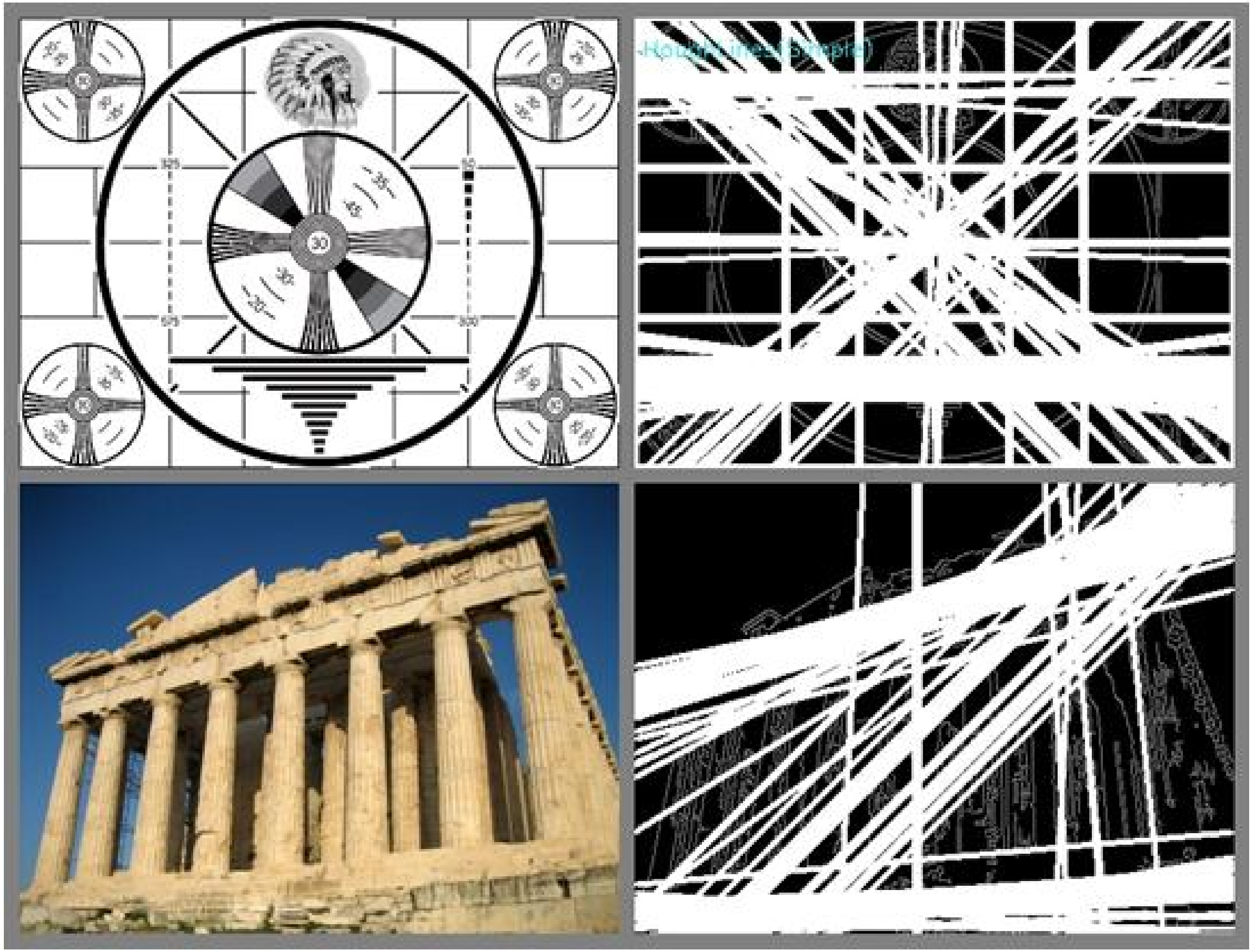
Distance Transform

- Distance field from edges of objects

Flood Filling



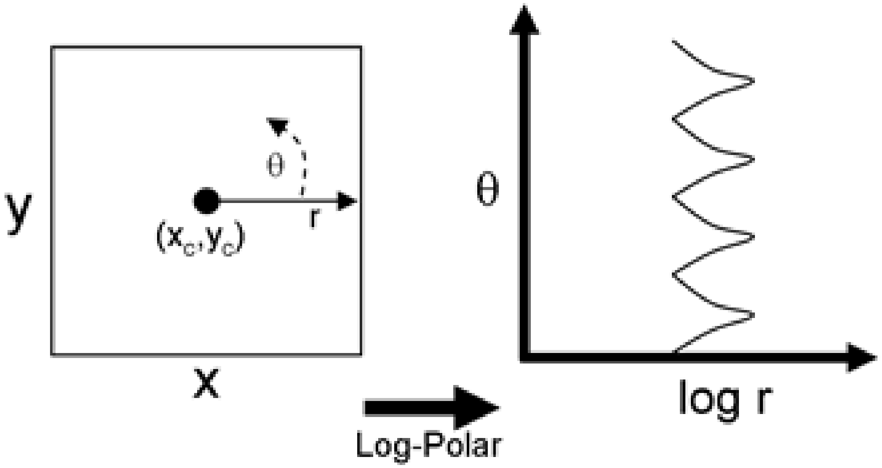
Hough Transform

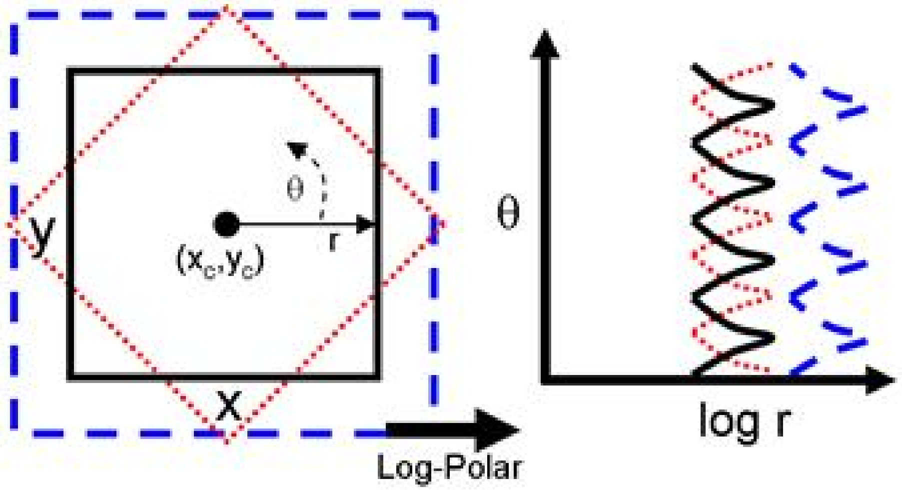


Gary Bradski, Adrian Kahler 2008

Space Variant vision: Log-Polar Transform

Screen shots by Gary Bradski, 2005





Scale Space

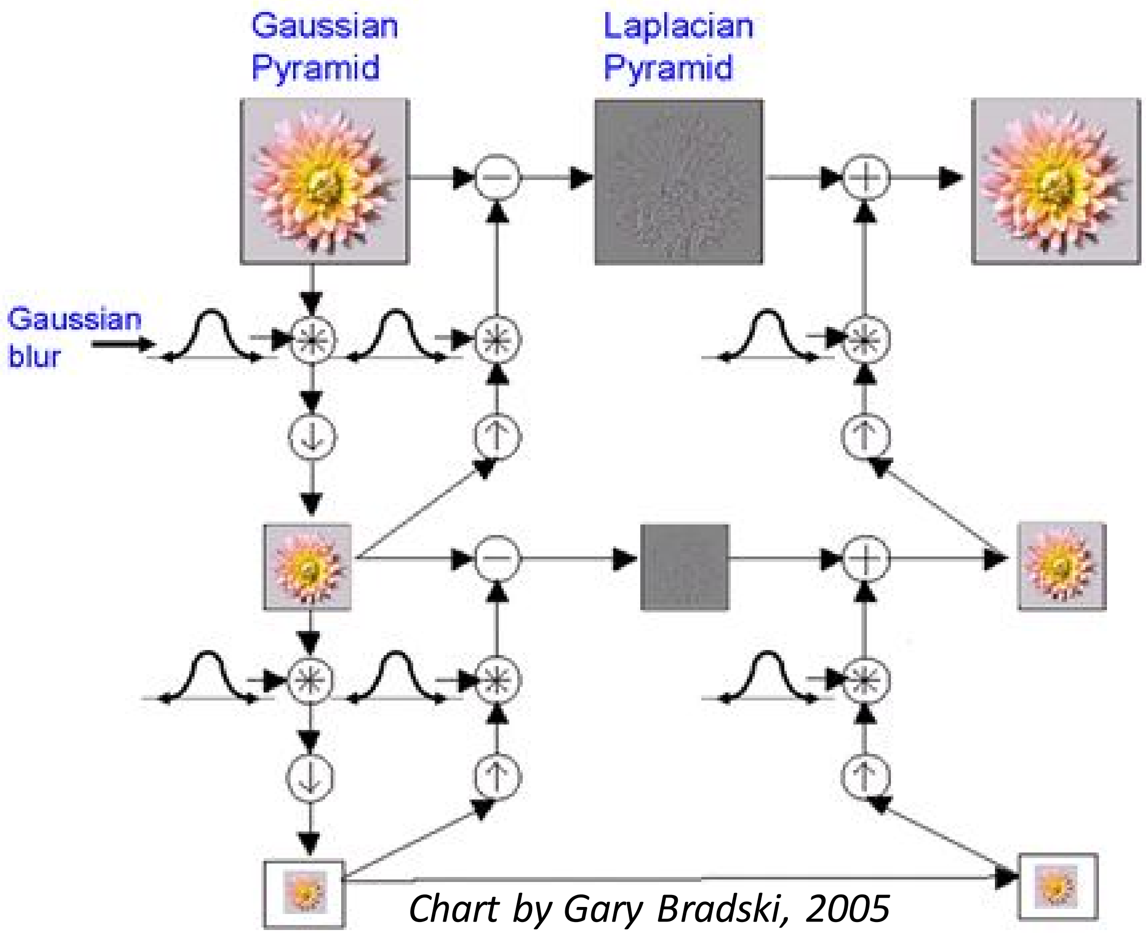
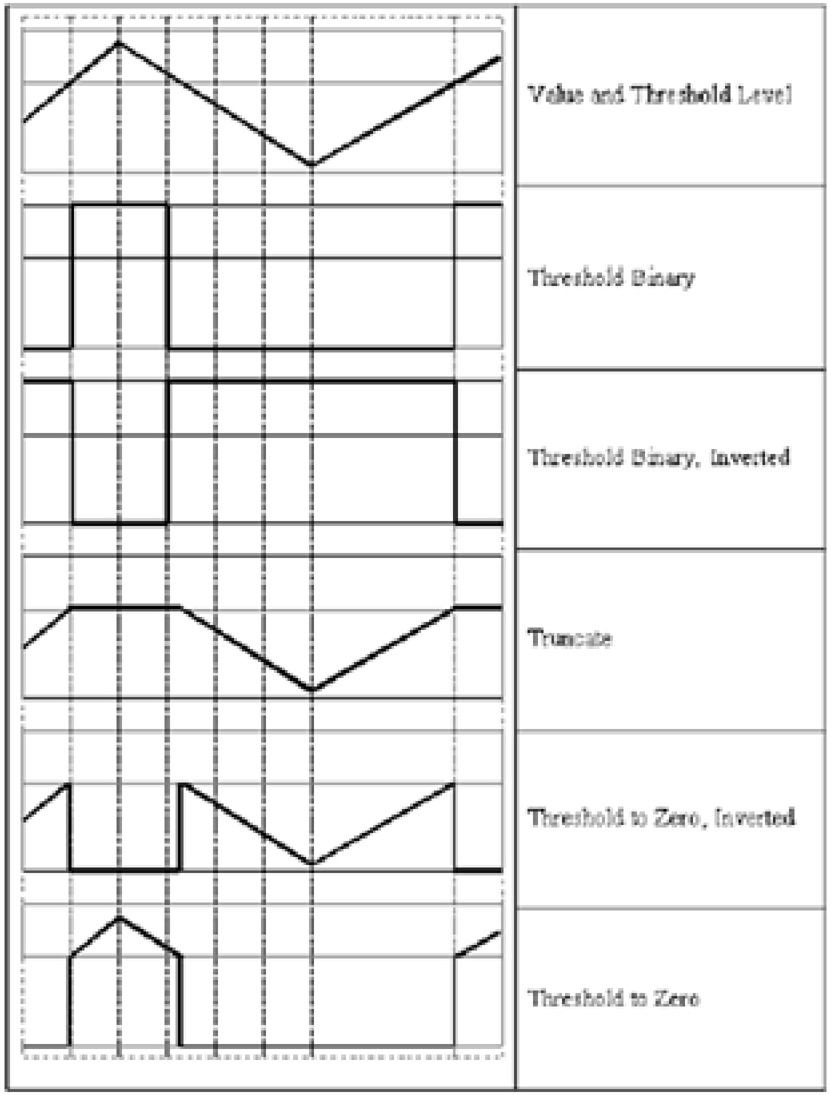


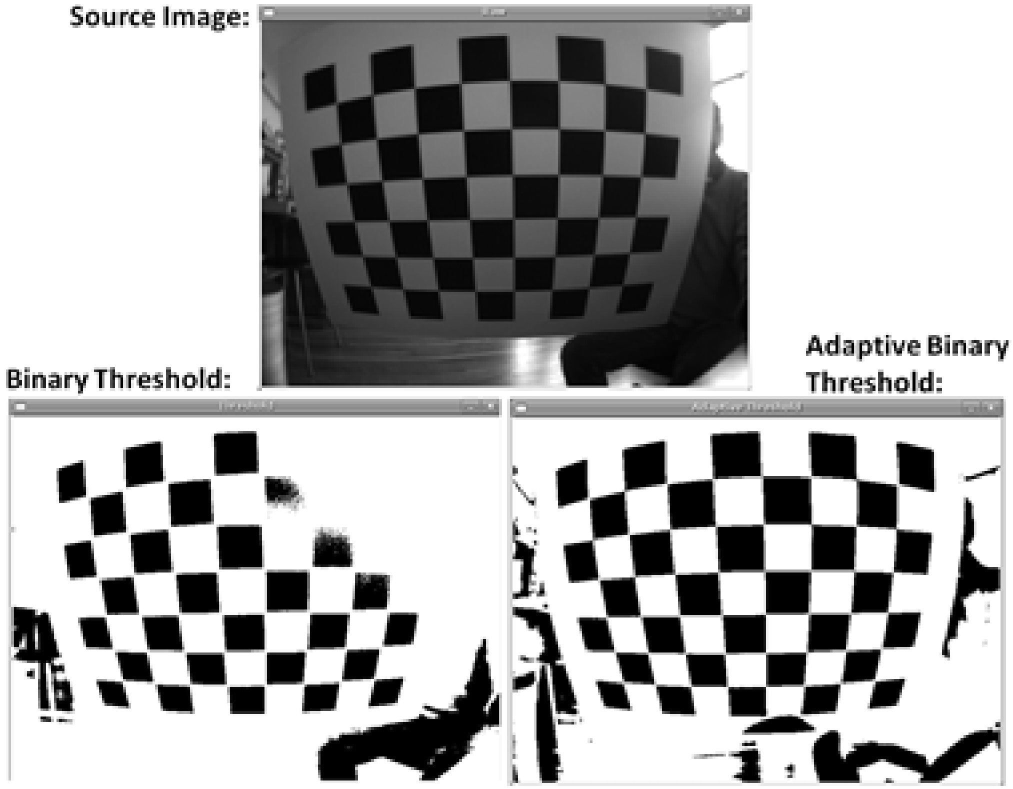
Chart by Gary Bradski, 2005

```
void cvPyrDown(
        IplImage*   src,
        IplImage*   dst,
        IplFilter     filter = IPL_GAUSSIAN_5x5);
```

```
void cvPyrUp(
        IplImage*   src,
        IplImage*   dst,
        IplFilter     filter = IPL_GAUSSIAN_5x5);
```

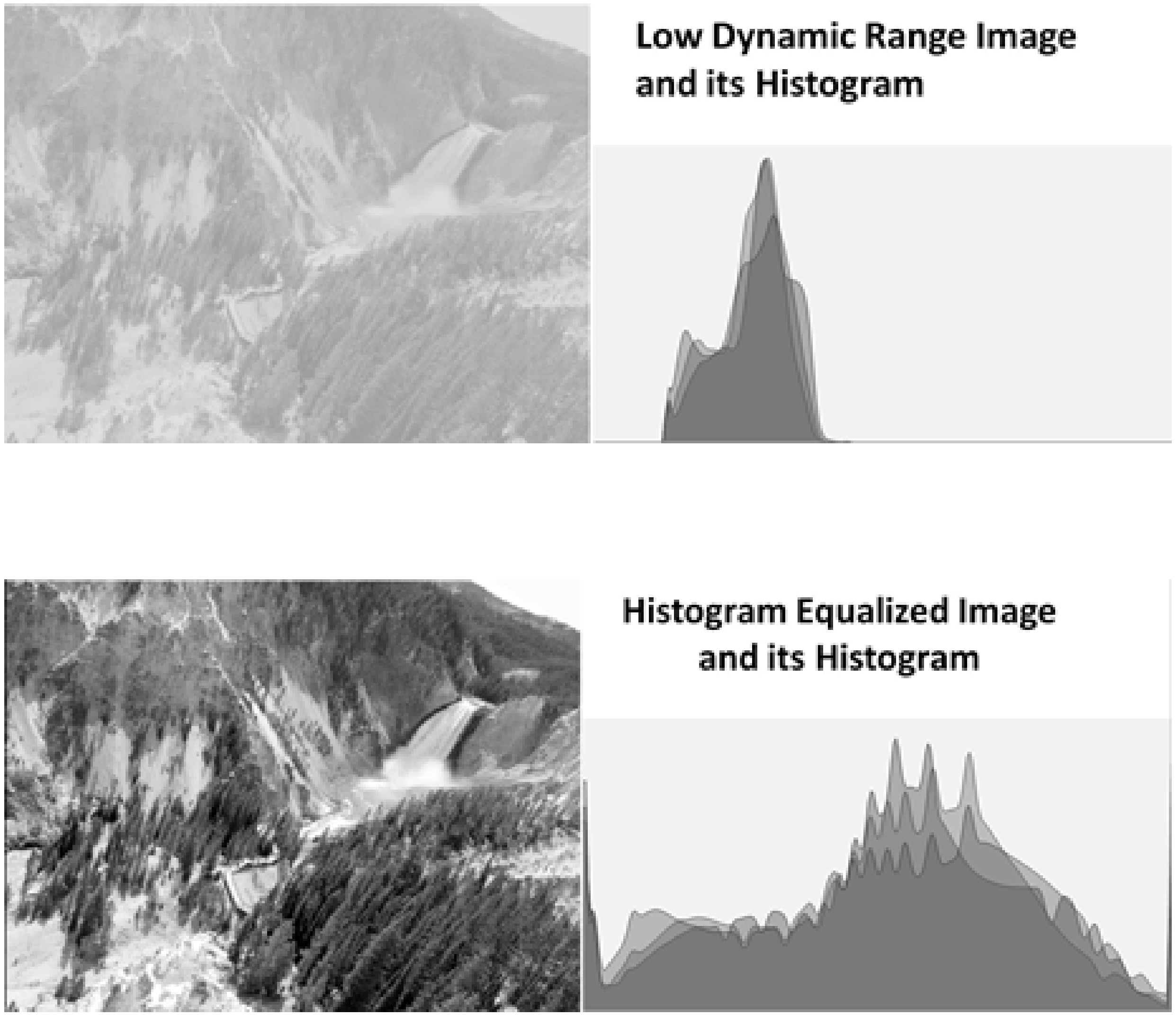
Thresholds





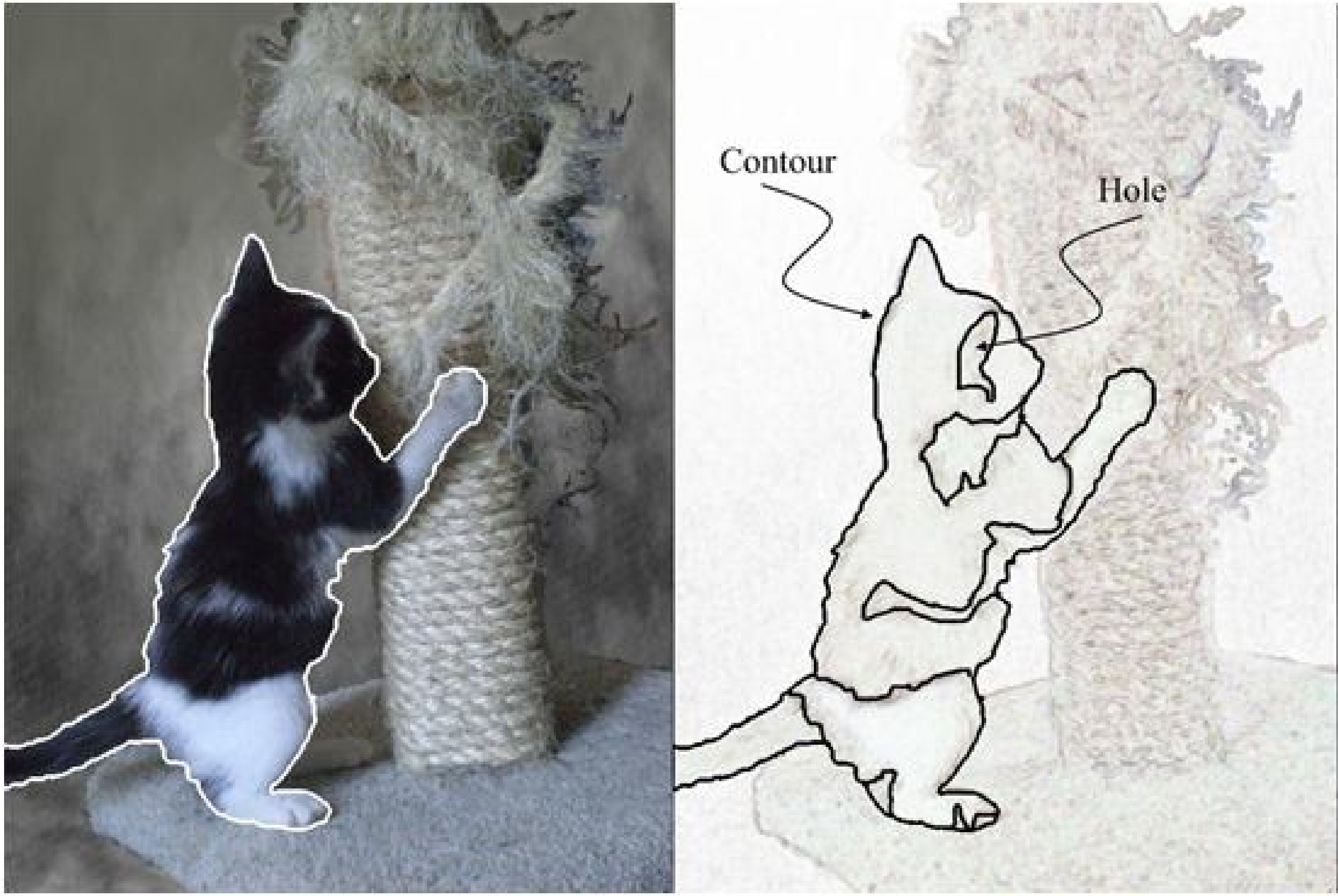
Screen shots by Gary Bradski, 2005

Histogram Equalization



Screen shots by Gary Bradski, 2005

Contours



Morphological Operations Examples

- Morphology - applying Min-Max. Filters and its combinations

Image I

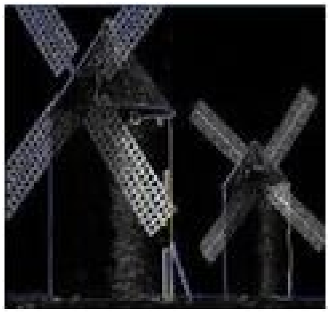
Erosion $I \Theta B$

Dilatation $I \oplus B$

Opening $I \circ B = (I \Theta B) \oplus B$

Closing $I \bullet B = (I \oplus B) \Theta B$

Grad(I)= $(I \oplus B) - (I \Theta B)$



TopHat(I)= $I - (I \Theta B)$

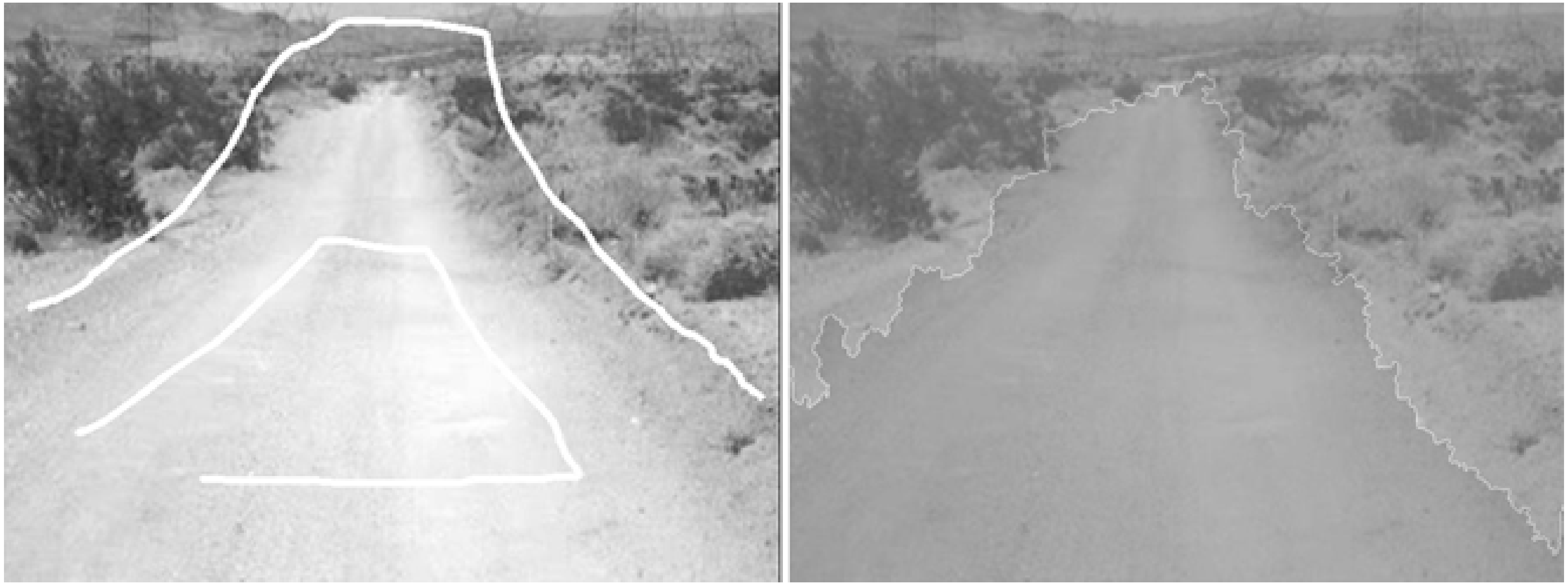
BlackHat(I)= $(I \oplus B) - I$

Image textures

- Inpainting:
- Removes damage to images, in this case, it removes the text.

Segmentation

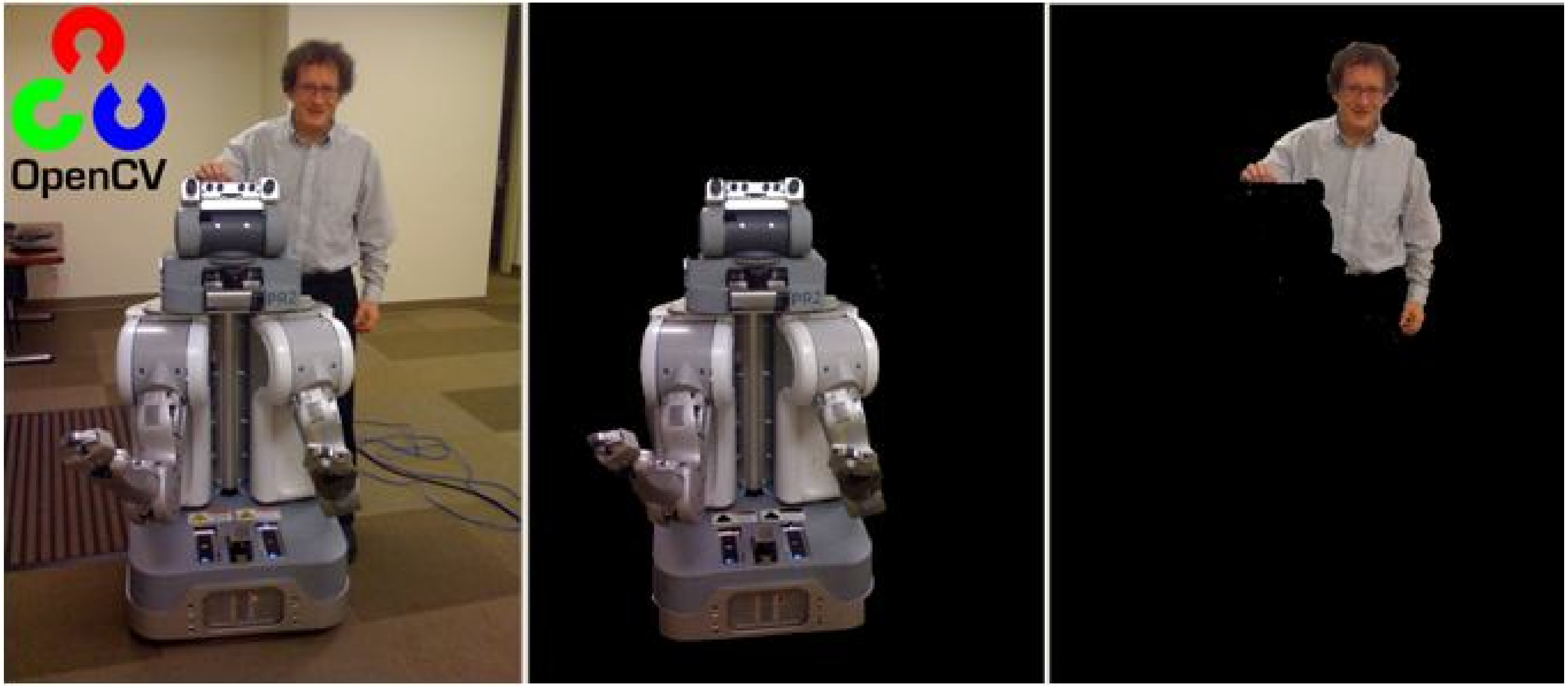
- Pyramid, mean-shift, graph-cut
- Here: Watershed



Screen shots by Gary Bradski, 2005

Recent Algorithms: GrabCut

- Graph Cut based segmentation

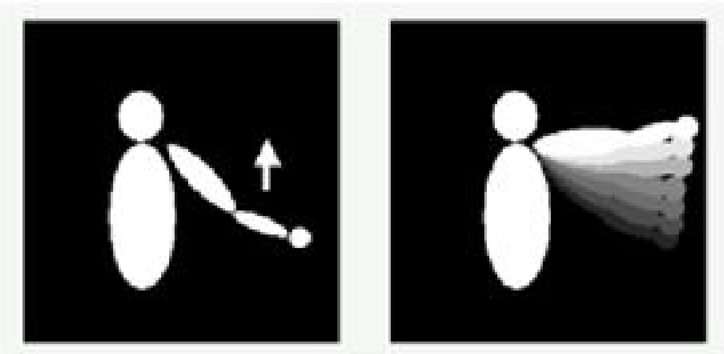


Images by Gary Bradski, © 2010

Motion Templates (work with James Davies)

- Object silhouette
- Motion history images
- Motion history gradients
- Motion segmentation algorithm

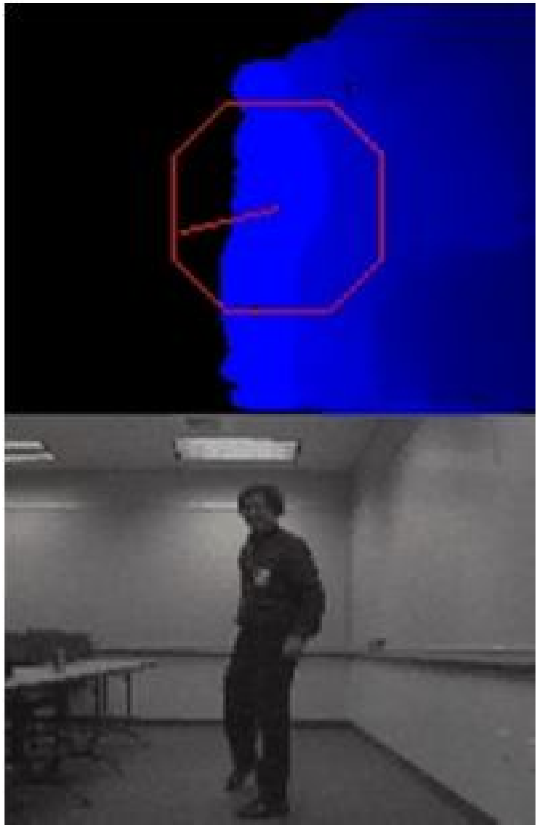
silhouette MHI



MHG

Charts by Gary Bradski, 2005

Segmentation, Motion Tracking
and
Gesture Recognition

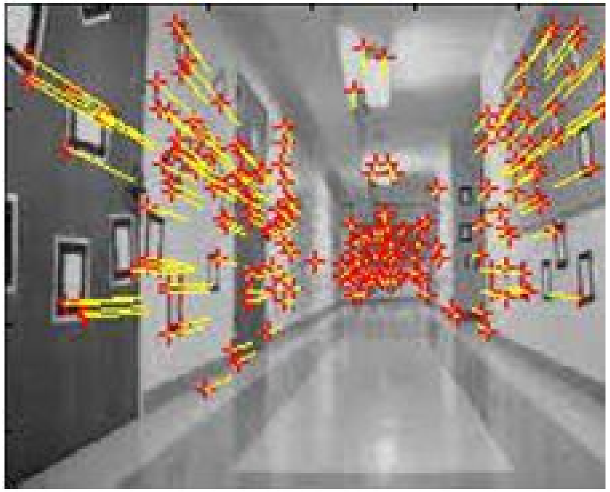
 

New Optical Flow Algorithms

```
// opencv/samples/c/lkdemo.c
int main(…){
…
CvCapture* capture = <…> ?
     cvCaptureFromCAM(camera_id) :
     cvCaptureFromFile(path);
if( !capture ) return -1;
for(;;) {
   IplImage*  frame=cvQueryFrame(capture);
   if(!frame) break;
   // … copy and process image
cvCalcOpticalFlowPyrLK( …)
   cvShowImage( "LkDemo", result );
   c=cvWaitKey(30); // run at ~20-30fps speed
   if(c >= 0) {
       // process key
 }}
cvReleaseCapture(&capture
```

lkdemo.c, 190 lines

(needs camera to run)

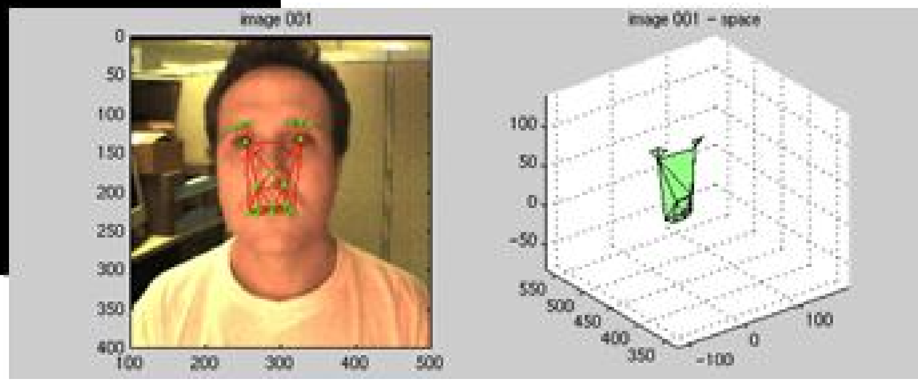


$$I(x+dx, y+dy, t+dt) = I(x,y,t);$$

$$-\partial I/\partial t = \partial I/\partial x \cdot (dx/dt) + \partial I/\partial y \cdot (dy/dt);$$

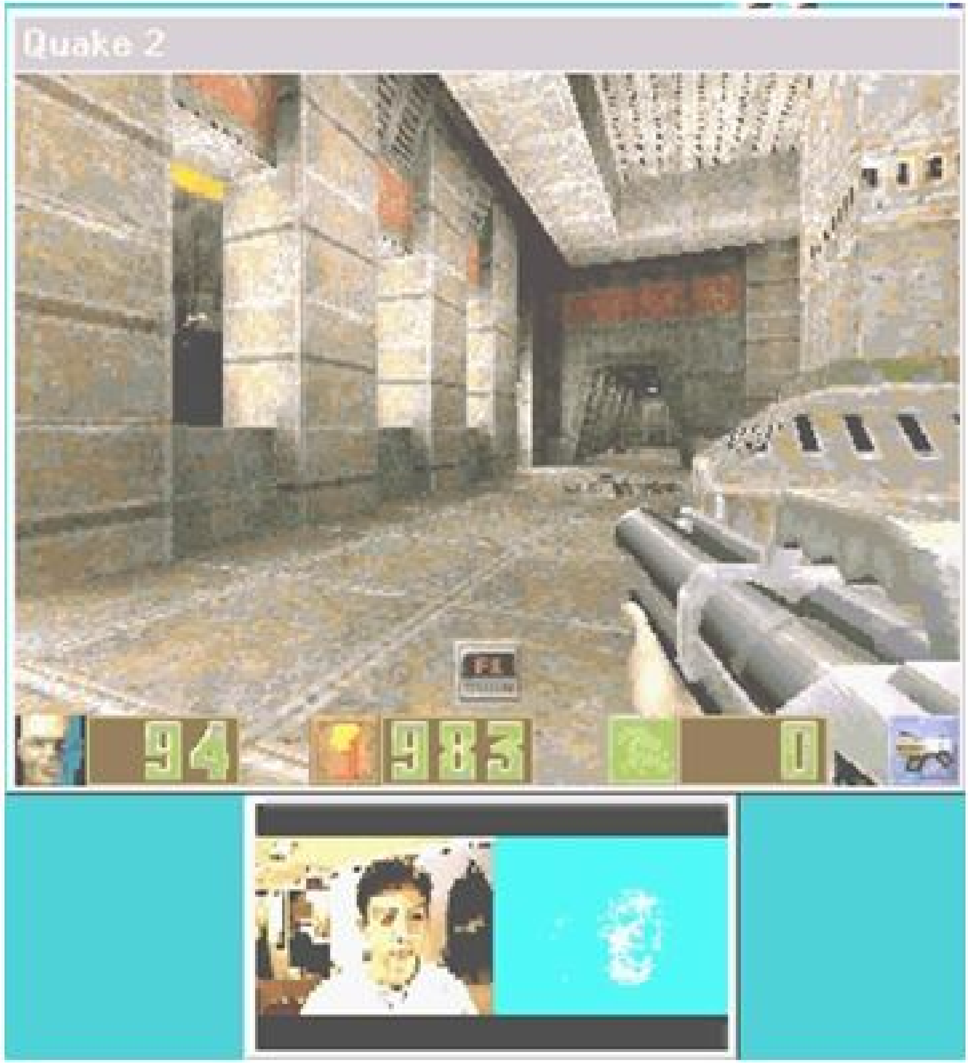
$$G \cdot \partial X = b,$$

$$\partial X = (\partial x, \partial y), G = \sum \begin{bmatrix} I_x^2, & I_x I_y \\ I_x I_y, & I_y^2 \end{bmatrix}, b = \sum I_t \begin{bmatrix} I_x \\ I_y \end{bmatrix}$$



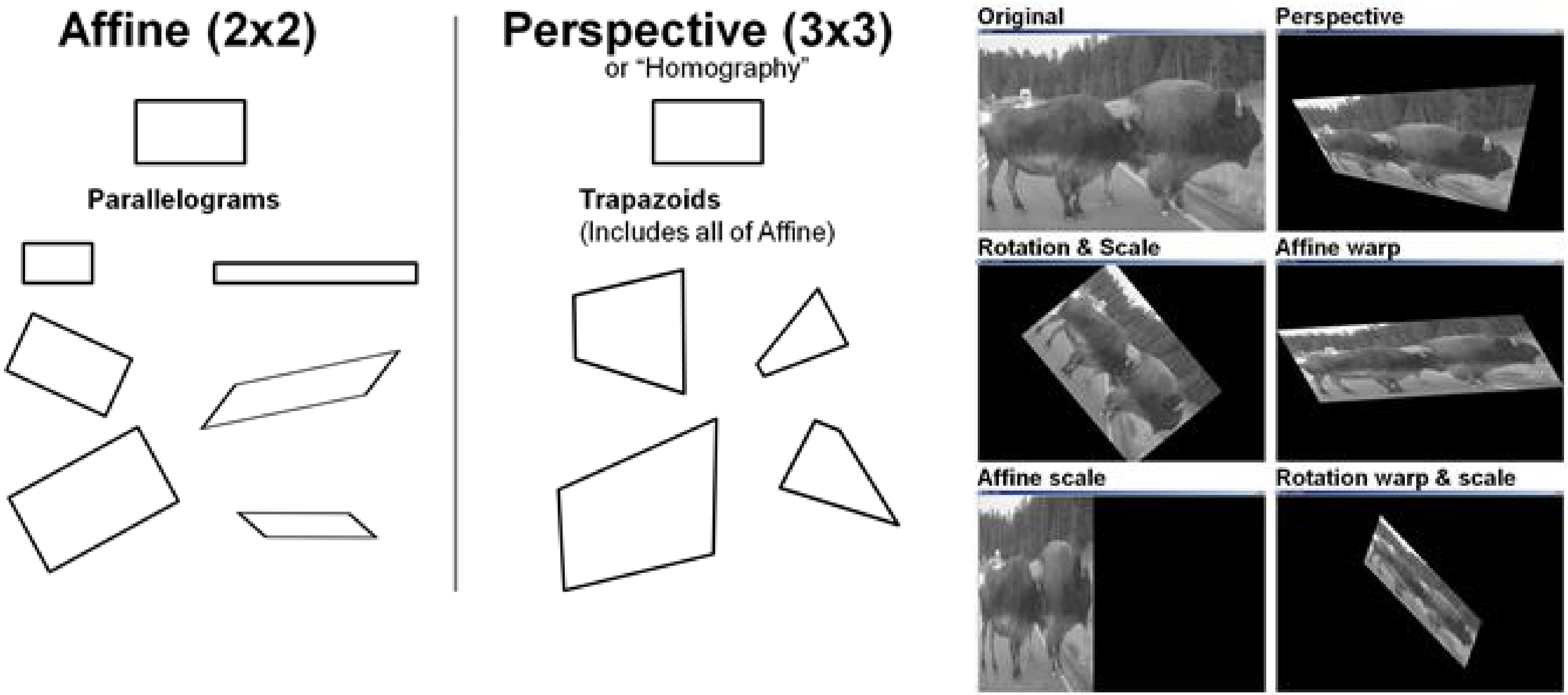
Tracking with CAMSHIFT

- Control game with head



Screen shots by Gary Bradski, 2005

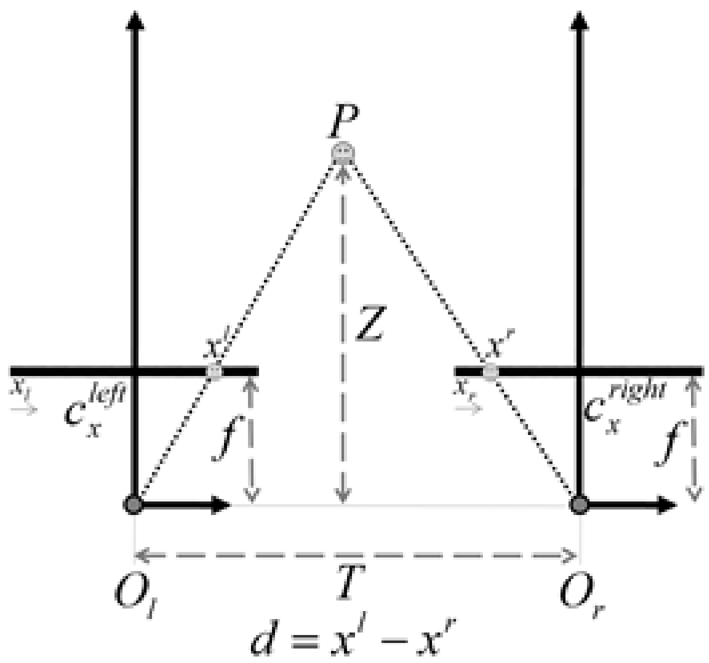
Projections



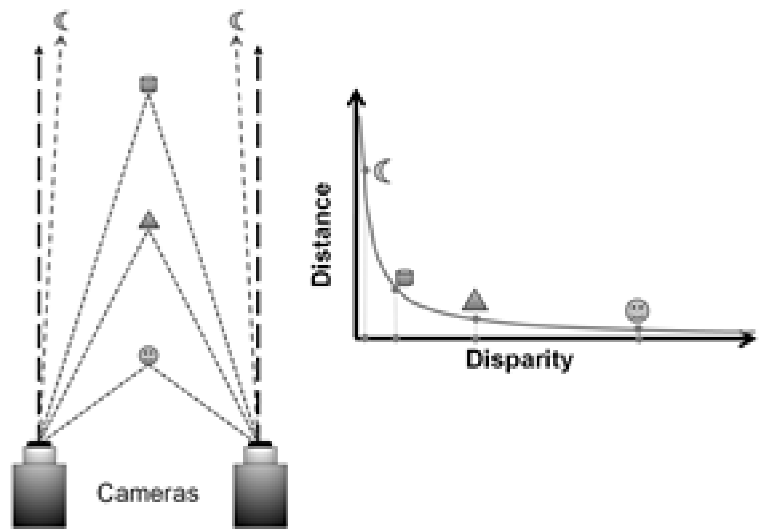
Screen shots by Gary Bradski, 2005

Stereo … Depth from Triangulation

- Involved topic, here we will just skim the basic geometry.
- Imagine two perfectly aligned image planes:

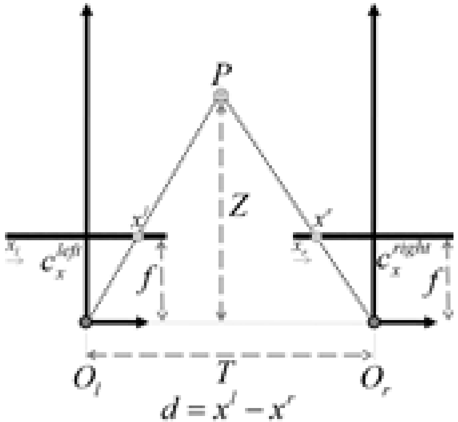


Depth "Z" and disparity "d" are inversly related:



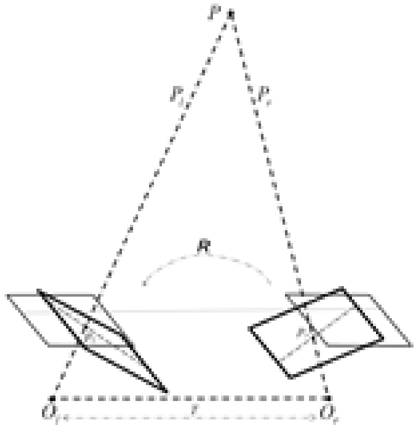
Stereo

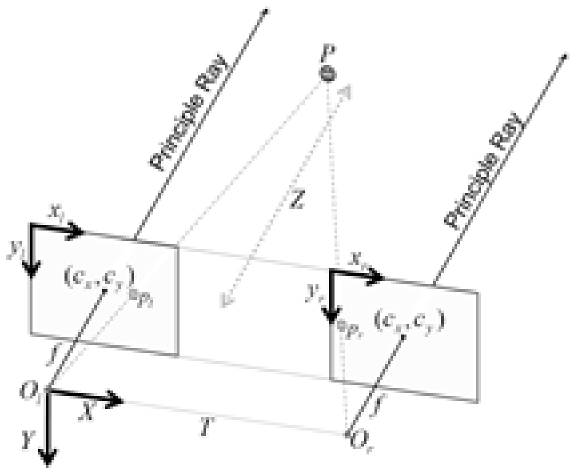
- In aligned stereo, depth is from similar triangles:



$$\frac{T-(x^l-x^r)}{Z-f}=\frac{T}{Z}\Rightarrow Z=\frac{fT}{x^l-x^r}$$

- Problem: Cameras are almost impossible to align
- Solution: Mathematically align them:

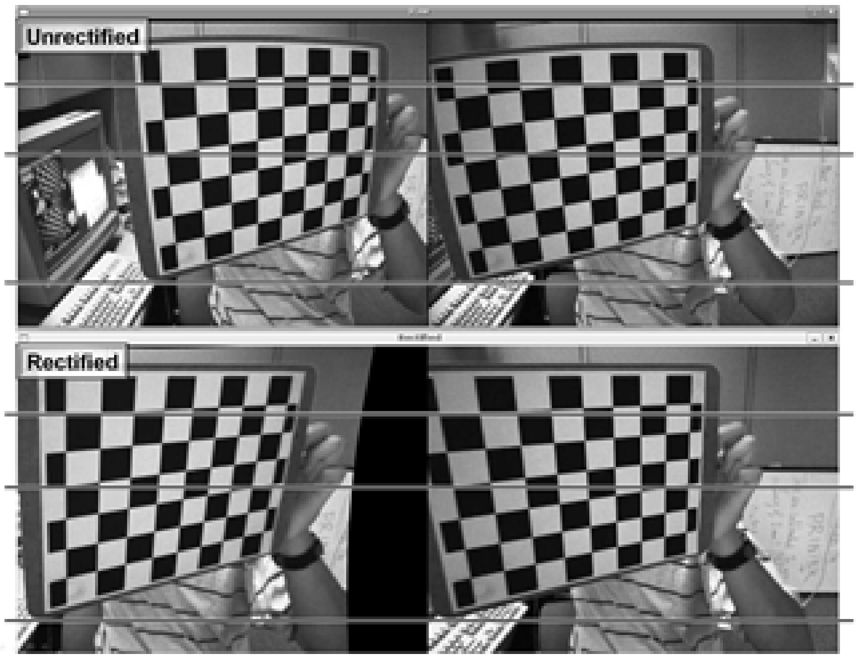


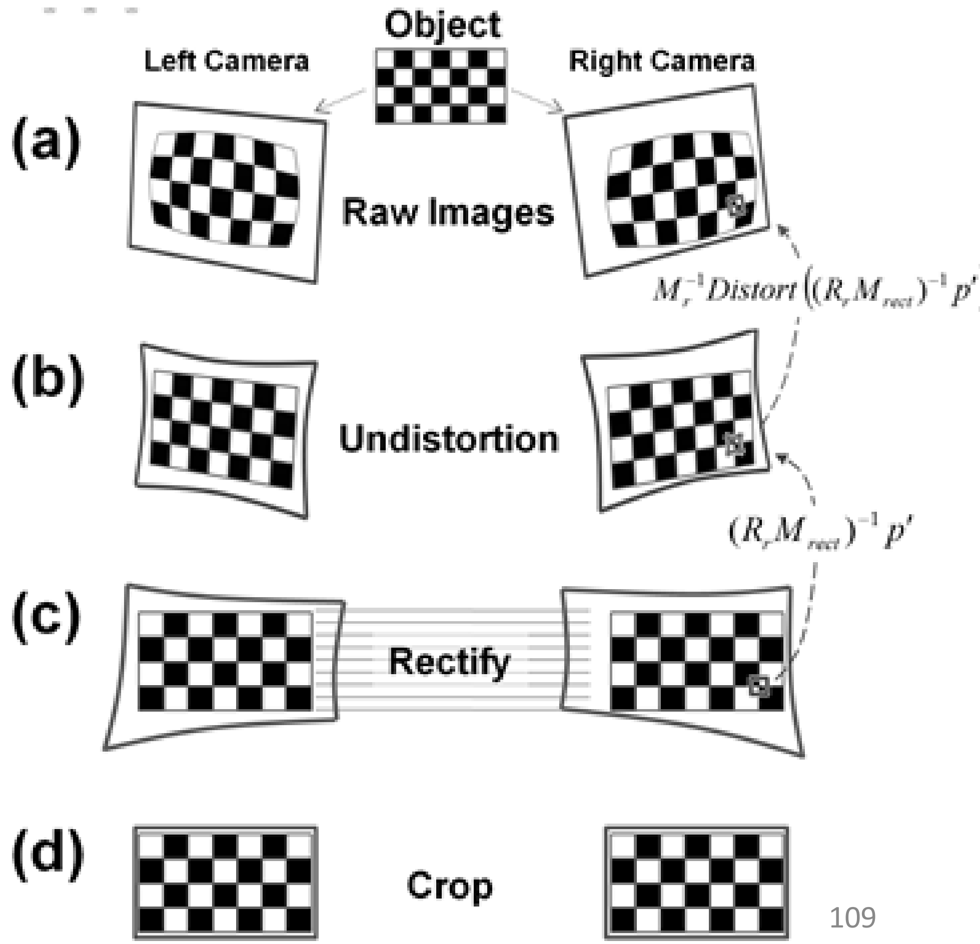


All: Gary Bradski and Adrian Kaehler: Learning OpenCV

Stereo Rectification

- Algorithm steps are shown at right:
- Goal:
  - Each row of the image contains the same world points
  - "Epipolar constraint"



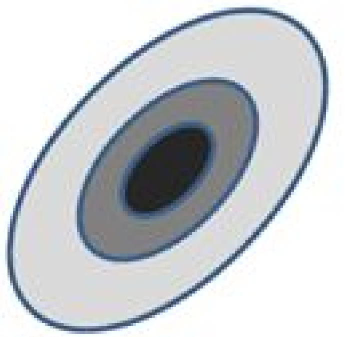


Outline

- OpenCV Overview
- Cheatsheet
- Simple Programs
- Features2D
- Applications

Features2d contents

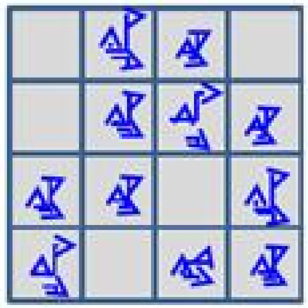
Detection



Detectors available

- SIFT
- SURF
- FAST
- STAR
- MSER
- HARRIS
- GFTT (Good Features To Track)

Description



Descriptors available

- SIFT
- SURF
- Calonder
- Ferns
- One way

Matching

Matchers available

- BruteForce
- FlannBased
- BOW

Matches filters

(under construction)

- Cross check
- Ratio check

Detector interfaces

```
class FeatureDetector
{
public:
   virtual ~FeatureDetector() {}

   // Detect keypoints in an image.
   virtual void detect( const Mat& image, vector<KeyPoint>& keypoints,
                        const Mat& mask=Mat() ) const = 0;
   // Detect keypoints in an image set.
   void detect( const vector<Mat>& imageCollection,
                vector<vector<KeyPoint> >& pointCollection,
                const vector<Mat>& masks=vector<Mat>() ) const;

   virtual void read( const FileNode& fn ) {}
   virtual void write( FileStorage& fs ) const {}

protected:
…
};
```

Creating a detector

- Statically

```
SurfFeatureDetector detector;
```

- Using class factory

```
cv::Ptr<FeatureDetector> detector =
   createFeatureDetector("SURF");
```

Running detector

```
Mat img = imread( "test.png" );
vector<KeyPoint> keypoints;

SurfFeatureDetector detector;
detector.detect( img, keypoints );
```

Descriptor interfaces

- For descriptors that can be represented as vectors in multidimensional space:

  DescriptorExtractor and DescriptorMatcher

- More general interface (one way, decision-tree-based descriptors):

  GenericDescriptorMatcher

DescriptorExtractor interfaces

```
class CV_EXPORTS DescriptorExtractor
{
public:
   virtual ~DescriptorExtractor() {}
   // Compute the descriptors for a set of keypoints in an image.
   virtual void compute( const Mat& image, vector<KeyPoint>& keypoints,
                                   Mat& descriptors ) const = 0;
   // Compute the descriptors for a keypoints collection detected in image collection.
   void compute( const vector<Mat>& imageCollection,
                       vector<vector<KeyPoint> >& pointCollection,
                       vector<Mat>& descCollection ) const;

   virtual void read( const FileNode& ) {}
   virtual void write( FileStorage& ) const {}
   virtual int descriptorSize() const = 0;
   virtual int descriptorType() const = 0;
protected:
…
};
```

DescriptorExtractor creating

- Statically

```
SurfDescriptorExtractor descriptorExtractor;
```

- Using class factory

```
cv::Ptr<DescriptorExtractor> descriptorExtractor =
    createDescriptorExtractor("SURF");
```

DescriptorExtractor running

```
Ptr<FeatureDetector> detector =
    createFeatureDetector("FAST");
Ptr<DescriptorExtractor> descriptorExtractor =
    createDescriptorExtractor("SURF");

vector<KeyPoint> keypoints;
detector->detect( img, keypoints );
Mat descriptors;
descriptorExtractor->compute( img, keypoints,
    descriptors );
```

DescriptorMatcher interfaces

- Two groups of match methods
  - to match descriptors of image pair
  - to match descriptors of one image to image set

- Each group consists from tree type methods
  - match()
  - knnMatch()
  - radiusMatch()

Matching of image pair

```
// detecting keypoints
SurfFeatureDetector detector;
vector<KeyPoint> keypoints1, keypoints2;
detector.detect( img1, keypoints1 );
detector.detect( img2, keypoints2 );

// computing descriptors
SurfDescriptorExtractor extractor;
Mat descriptors1, descriptors2;
extractor.compute( img1, keypoints1, descriptors1 );
extractor.compute( img2, keypoints2, descriptors2 );

// matching descriptors
BruteForceMatcher<L2<float> > matcher;
vector<DMatch> matches;
matcher.match( descriptors1, descriptors2, matches );
```

Visualize keypoints

```
Mat img_points;
drawKeypoints( img, keypoints, img_points );
namedWindow( “keypoints”, 1 );
imshow( “keypoints”, img_points );
waitKey();
```

Visualize matches

```
Mat img_matches;
drawMatches( img1, keypoints1,
             img2, keypoints2, img_matches);
namedWindow( “matches”, 1 );
imshow( “matches”, img_matches );
waitKey();
```

Running the sample

- Download OpenCV
- Compile
- Run matcher_simple:

  bin/matcher_simple ../../opencv/samples/c/box.png ../../opencv/samples/c/box_in_scene.png

- Select a detector that gives the maximum number of keypoints
- Switch SIFT and SURF descriptors

Cross-check outlier match filtering

```
BruteForceMatcher<L2<float> > descriptorMatcher;
vector<DMatch> filteredMatches12, matches12, matches21;
descriptorMatcher.match( descriptors1, descriptors2, matches12 );
descriptorMatcher.match( descriptors2, descriptors1, matches21 );

for( size_t i = 0; i < matches12.size(); i++ )
{
   DMatch forward = matches12[i];
   DMatch backward = matches21[forward.trainIdx];
   if( backward.trainIdx == forward.queryIdx )
      filteredMatches12.push_back( forward );
}
```

Ratio test to filter matches

$$Ratio = \frac{MinDist\,1}{MinDist\,2} \in (0,1]$$ (less is better)

$$if \;\; Ratio < threshold(0.3) \;\; \Rightarrow inlier, \; else \; outlier$$

Calculating inliers (planar objects case)

- Detect keypoints
- Find matches using descriptors
- Filter matches using cross-check
- Calculate best homography
- Filter outliers
- Run

  bin/descriptor_extractor_matcher SURF SURF ../../opencv/samples/c/box.png ../../opencv/samples/c/box_in_scene.png 3

  The last parameter is the reprojection threshold for RANSAC

OpenCV and ROS

- Opencv2 package to fetch and compile opencv
- Messages:
  - sensor_msgs::Image
  - sensor_msgs::CameraInfo
- cv_bridge to convert between messages and images
- image_geometry::PinholeCameraModel and image_geometry::StereoCameraModel to manage 2d <-> 3d conversions

Q&A

- Foils will be available at http://itseez.com