Satellite Motion Determination Using Image Processing

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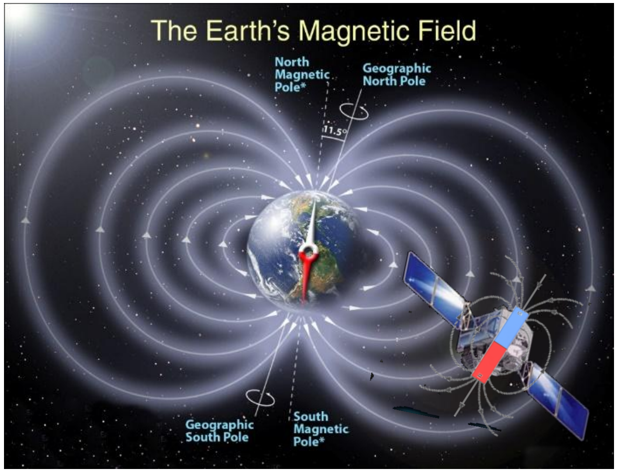
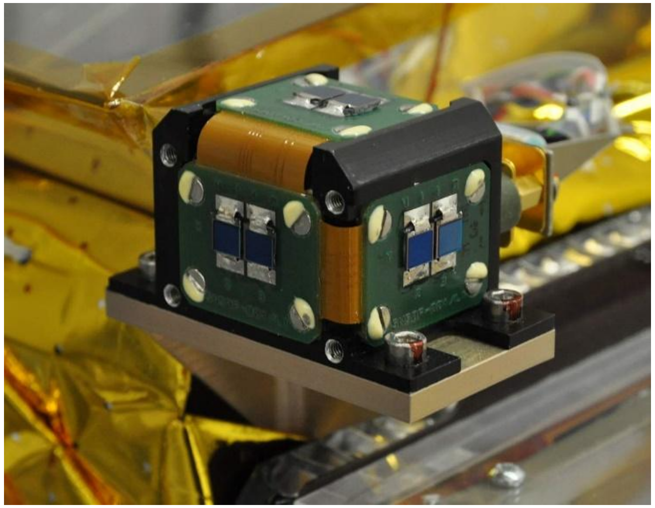
- **Attitude determination using a star tracker**
- **Relative motion determination**
- **Image processing in a laboratory environment**
- **Conclusions**

Attitude sensors

The most frequently used

- **Vector measurement sensors**
  - **Magnetometer**
  - **Sun sensor**
  - **Infrared sensor**
  - **Star tracker**

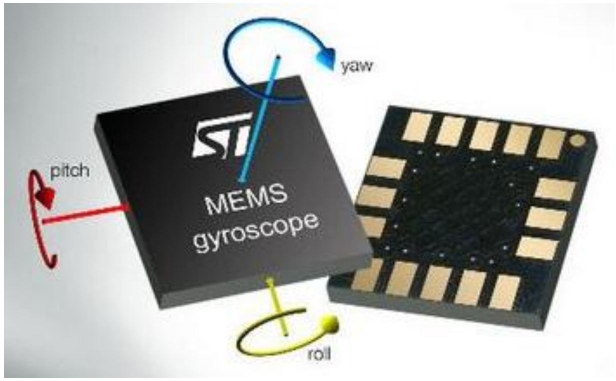


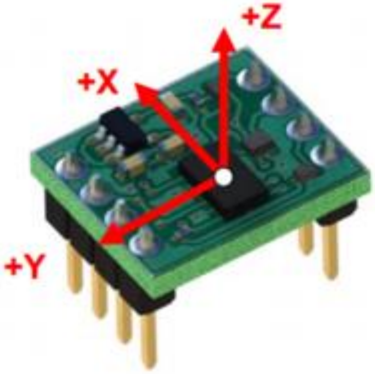


Attitude sensors

The most frequently used

- **Inertial measurement sensors**
  - **Angular velocity sensor**
  - **Accelerometers**

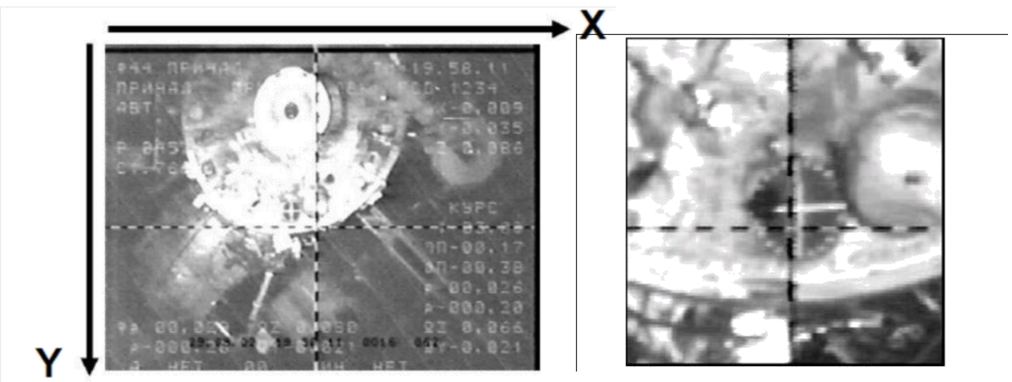




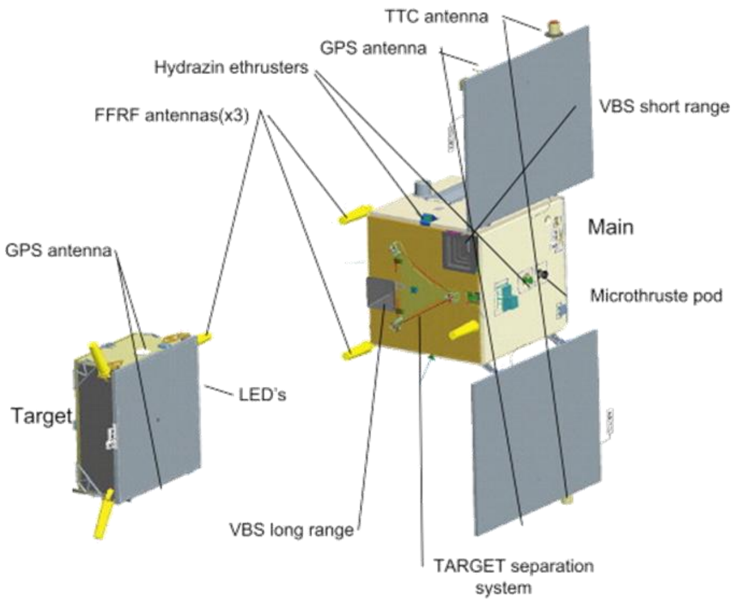
Attitude sensors

The most frequently used

- **Relative attitude determination in Formation Flight**
  - **Image processing**
  - **Radio antennas measurements**
  - **Laser systems**

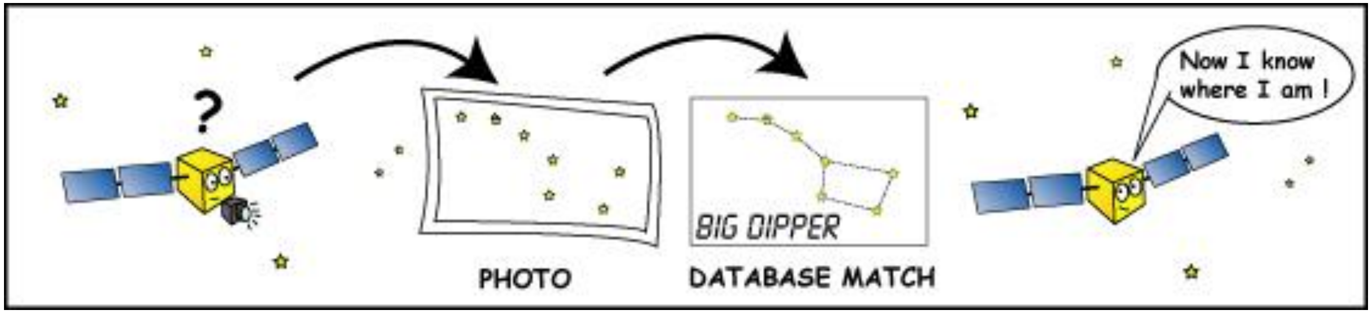


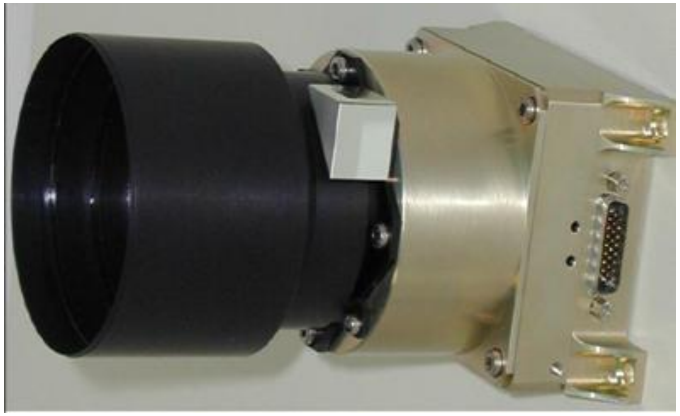
Cargo satellite “Progress” docking to ISS

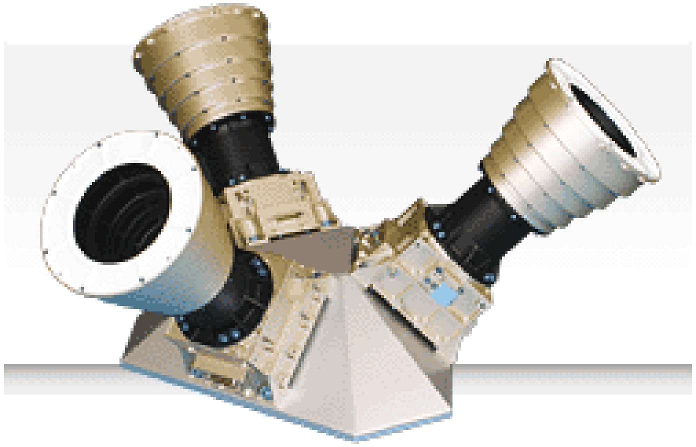


Star tracker

- Angular distances between observed stars are calculated.
- The observed stars recognition with star catalog is executed.
- The optical axis orientation and the rotation angle about this axis are determined.







Star recognition algorithms testing

Algorithms features to be defined:

- The center of star image computation method.
- The number of stars in catalog.
- The star brightness accounting.

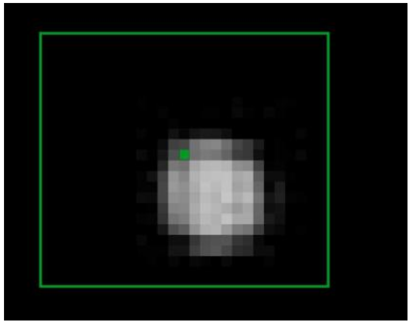
Problems:

- Does not work under Sun exposure.
- The attitude determination accuracy depends on angular velocity.
- The first recognition can take a long time.

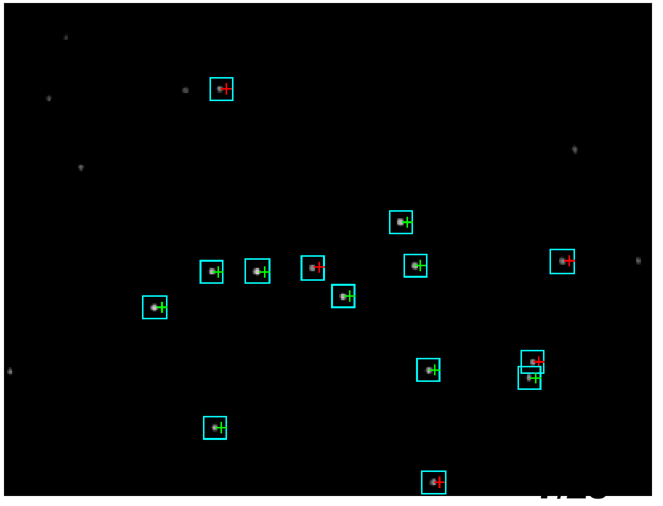
Star image

Star center calculation

$$x_c = \frac{\sum x_i I_i}{\sum I_i}, \quad y_c = \frac{\sum y_i I_i}{\sum I_i}$$



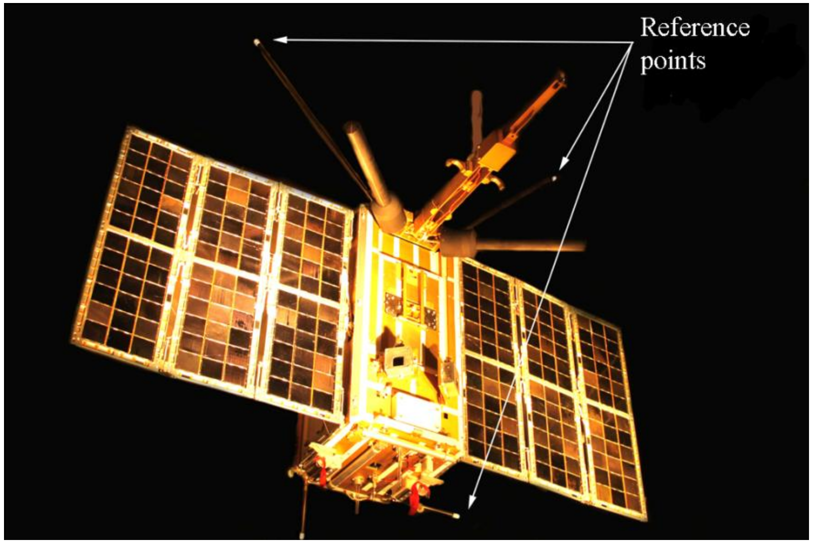
Star recognitions results

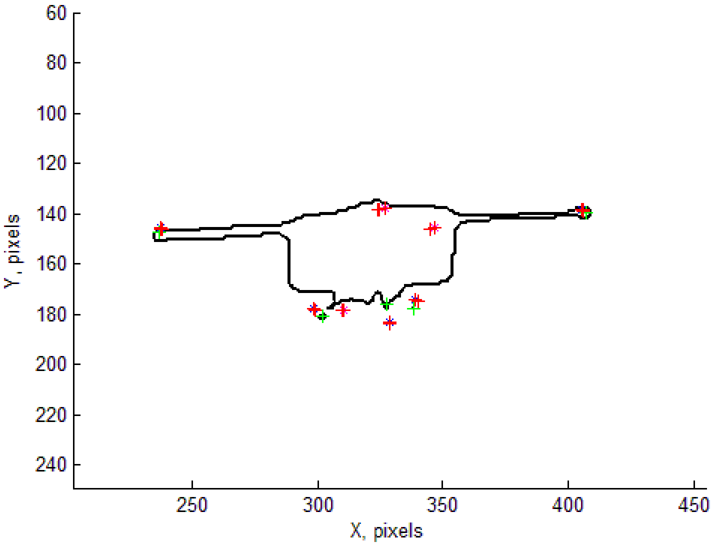


Relative motion determination in formation flight

Image processing assumptions:

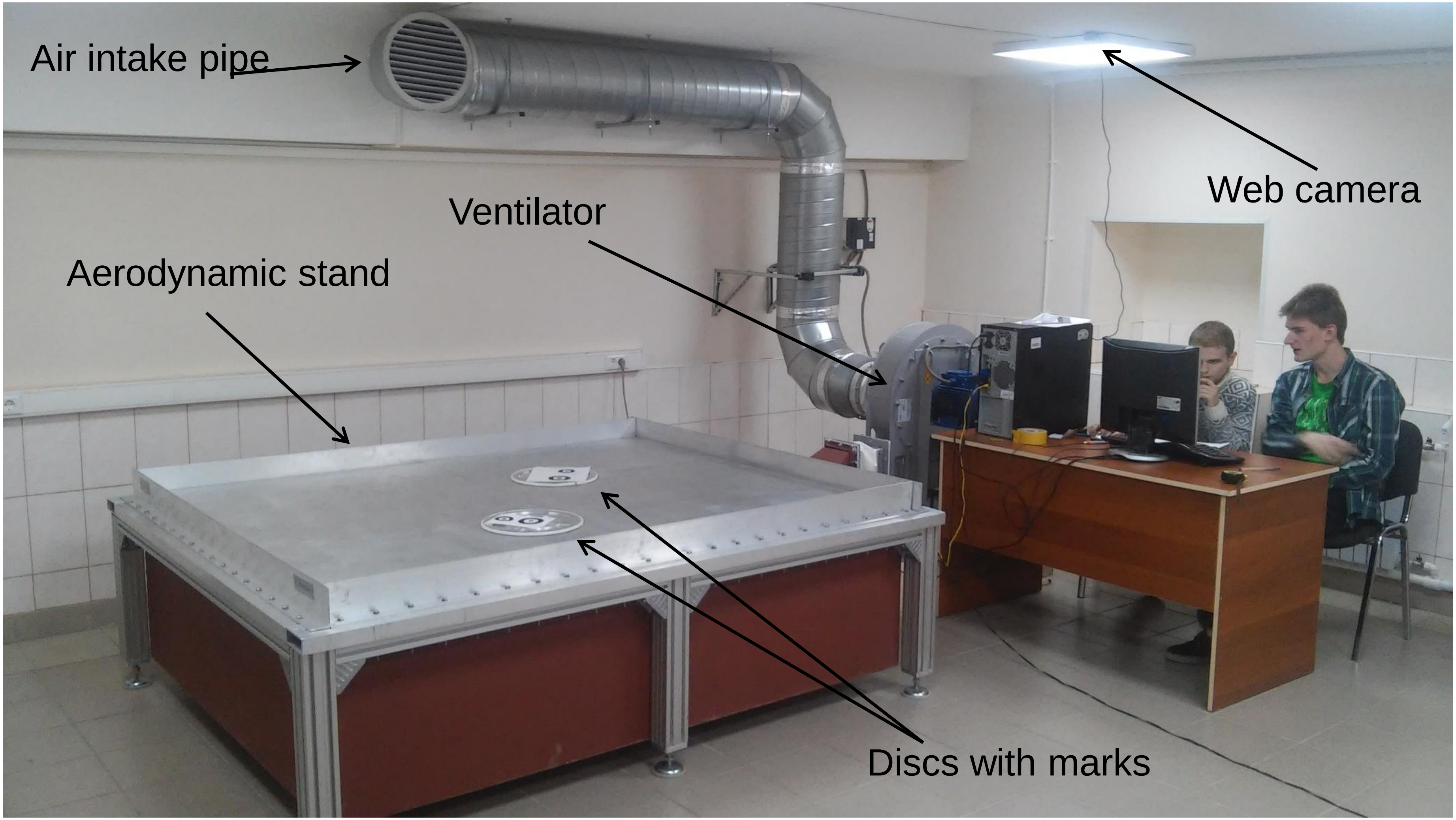
- The camera is installed on board of the 1st satellite and observes the 2nd.
- The shape and the reflection properties of the 2nd satellite are known.





Process of relative position and attitude determination. Red stars are the initial ref. point position, green crosses are measured position, red ones are estimated by LSQ method.

KIAM experimental stand



Camera calibration

- Intrinsic parameters
  - Focal length
  - Principle point offset
  - Distortion coefficients
- Extrinsic parameters
  - Transition vector
  - Rotation matrix

Camera model

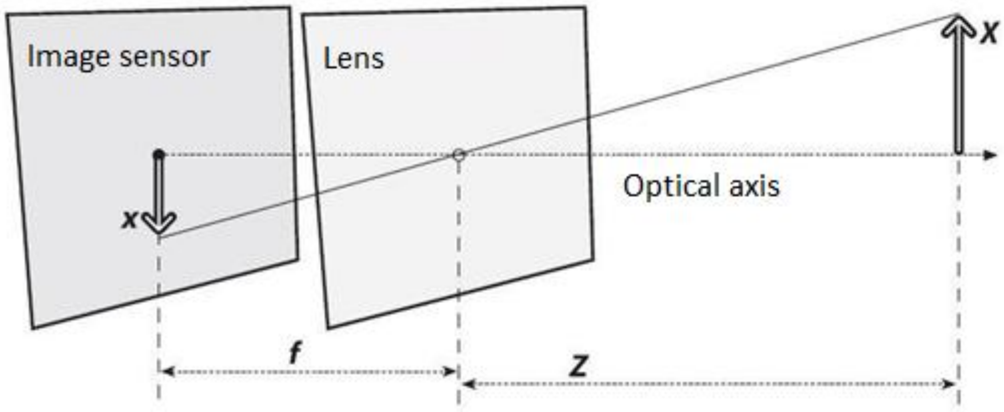
From triangles similarity: $x = f\,\dfrac{X}{Z}$

Taking pixel size into account:

$$f_x = s_x f \qquad\qquad f_y = s_y f$$

Considering principle point offset:

$$x = f_x \frac{X}{Z} + c_x \qquad\qquad y = f_y \frac{Y}{Z} + c_y$$



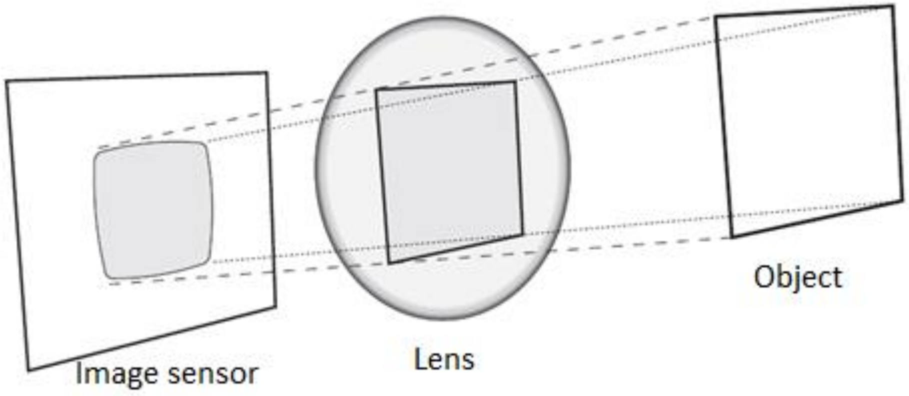
Pinhole camera model

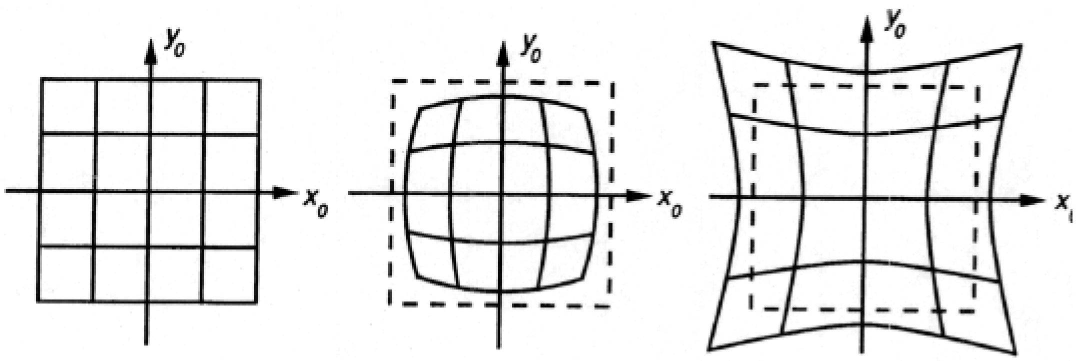
Distortions

First terms of Taylor series:

$$x_{corr} = x\left(1 + k_1 r^2 + k_2 r^4\right),$$

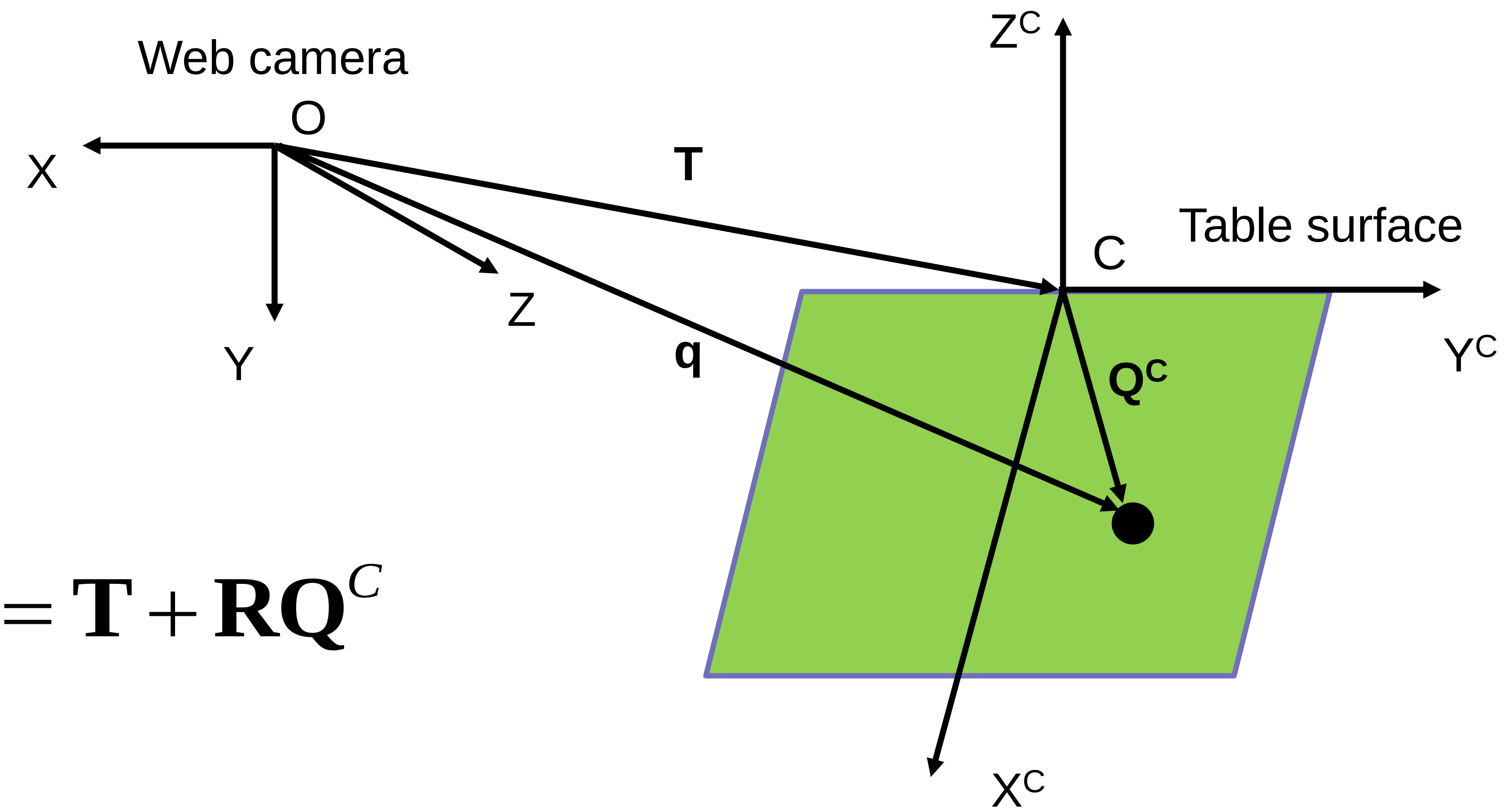
$$y_{corr} = y\left(1 + k_1 r^2 + k_2 r^4\right).$$





No Distortion   Barrel Distortion   Pincushion Distortion

Extrinsic camera parameters

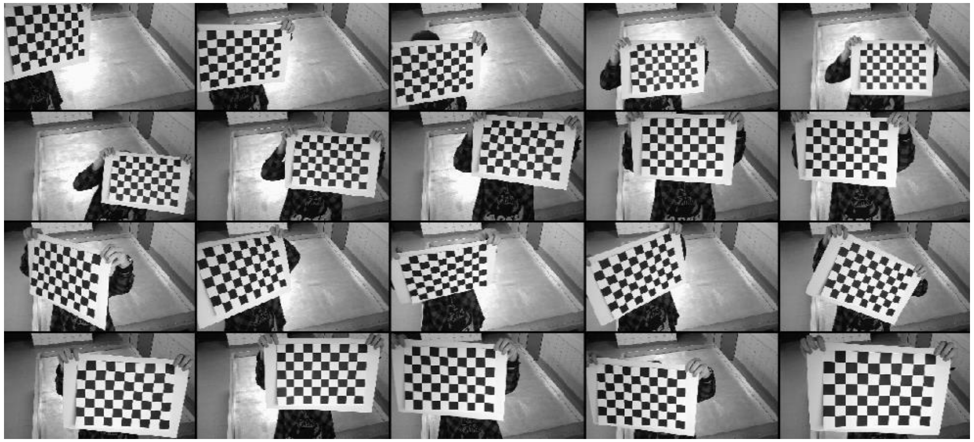


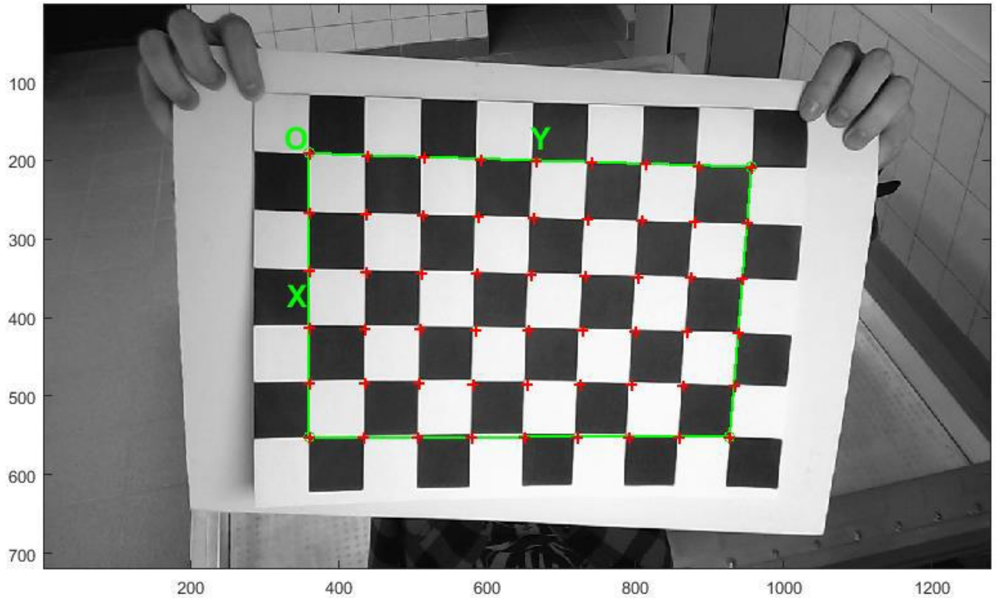
$$\mathbf{q} = \mathbf{T} + \mathbf{R}\mathbf{Q}^{C}$$

Coordinate systems transformations

Camera parameters determination

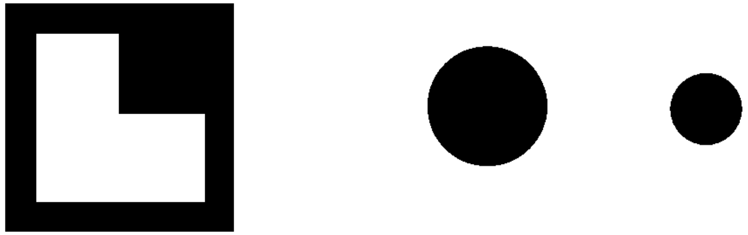
- A series of chessboard images is considered as input
- Matlab Calibration Toolbox is used for calibration
- Least squares method is used to calculate the parameters



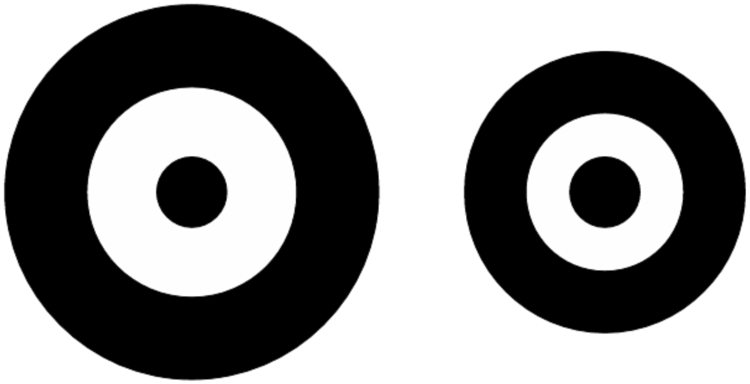


Marks recognition

- Different objects differ in distance between the centers of circles
- Nested contours provide high recognition accuracy



Initial mark versions



Final version of a mark

Mark recognition algorithm

Get an image from the camera

Convert to binary image

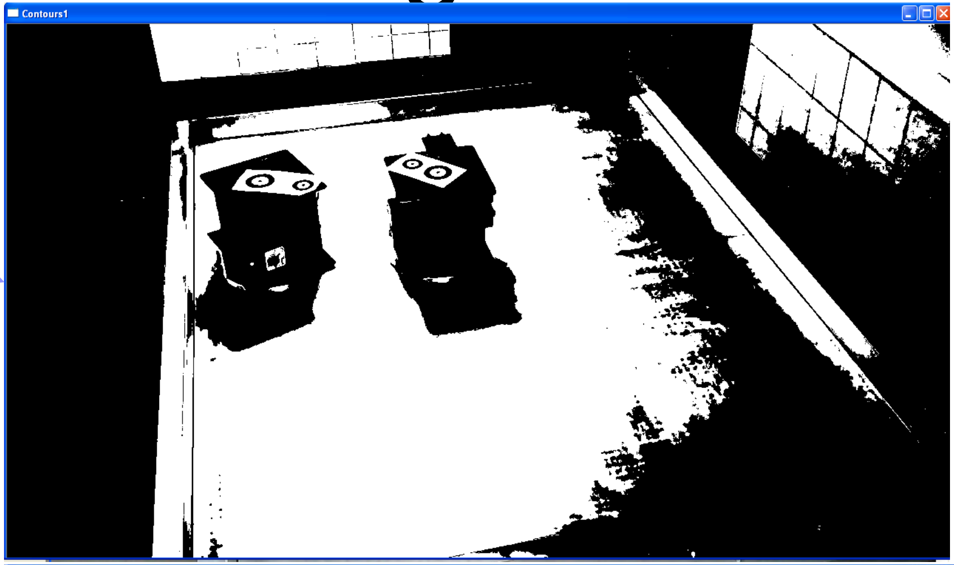
Find contours

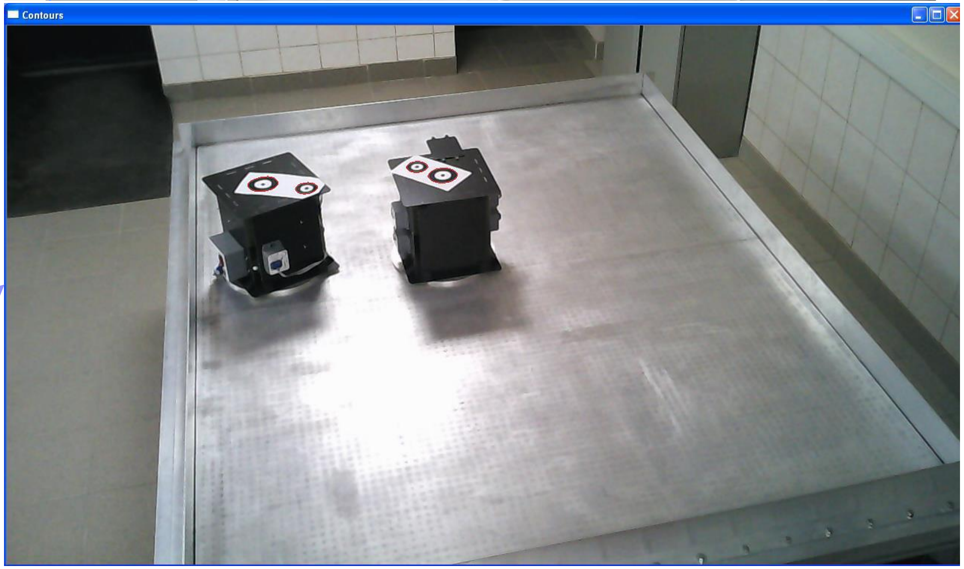
Check contour perimeter

Check contour circularity

Check for nested contours

Group circles in marks





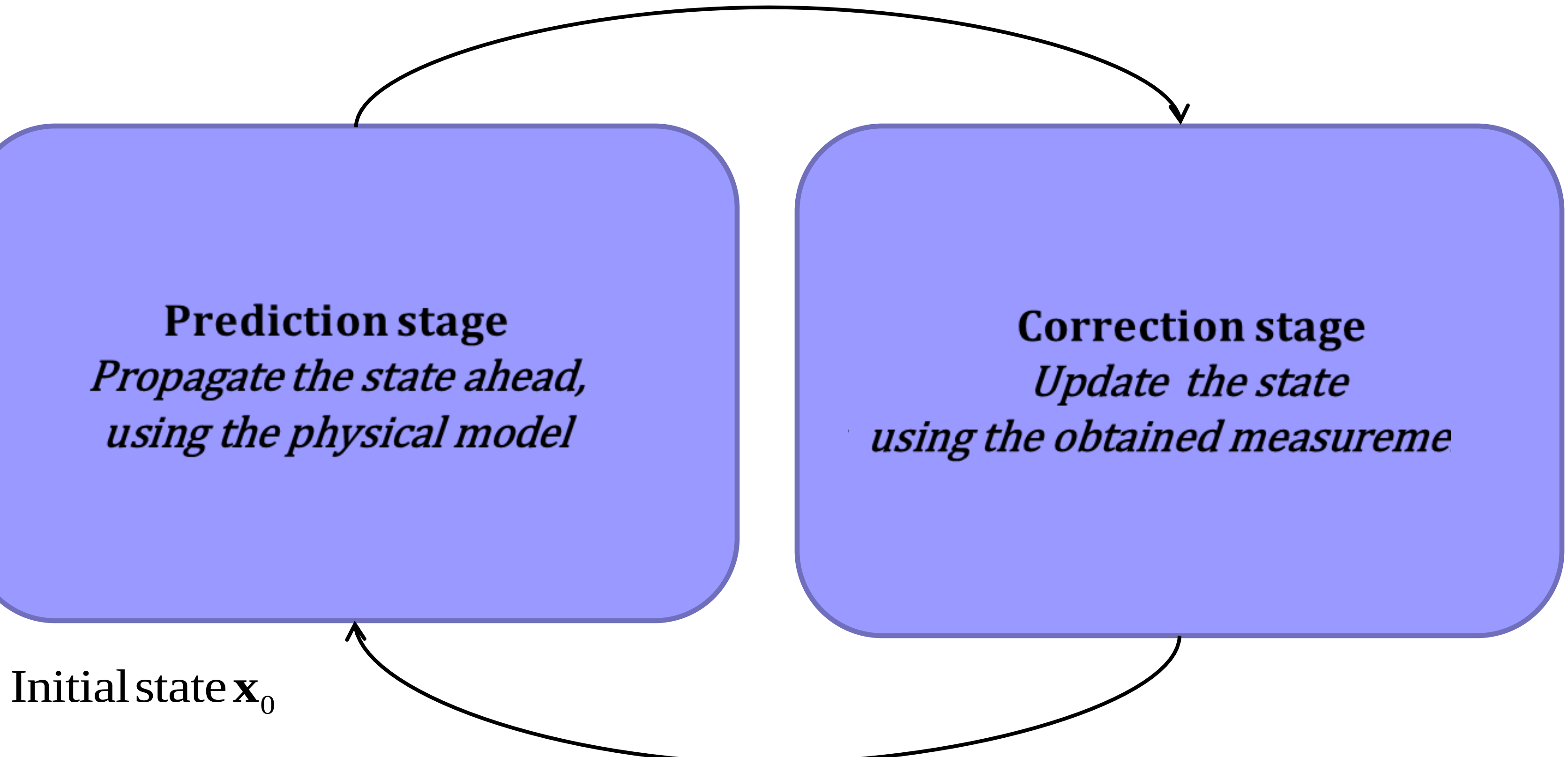
Kalman filter

State vector:

$$\mathbf{x} = (x, y, \varphi, v_x, v_y, \omega)^T$$

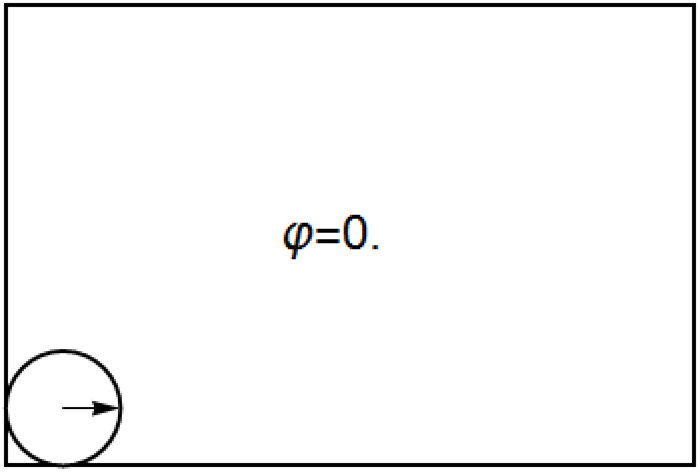
Measurements vector:

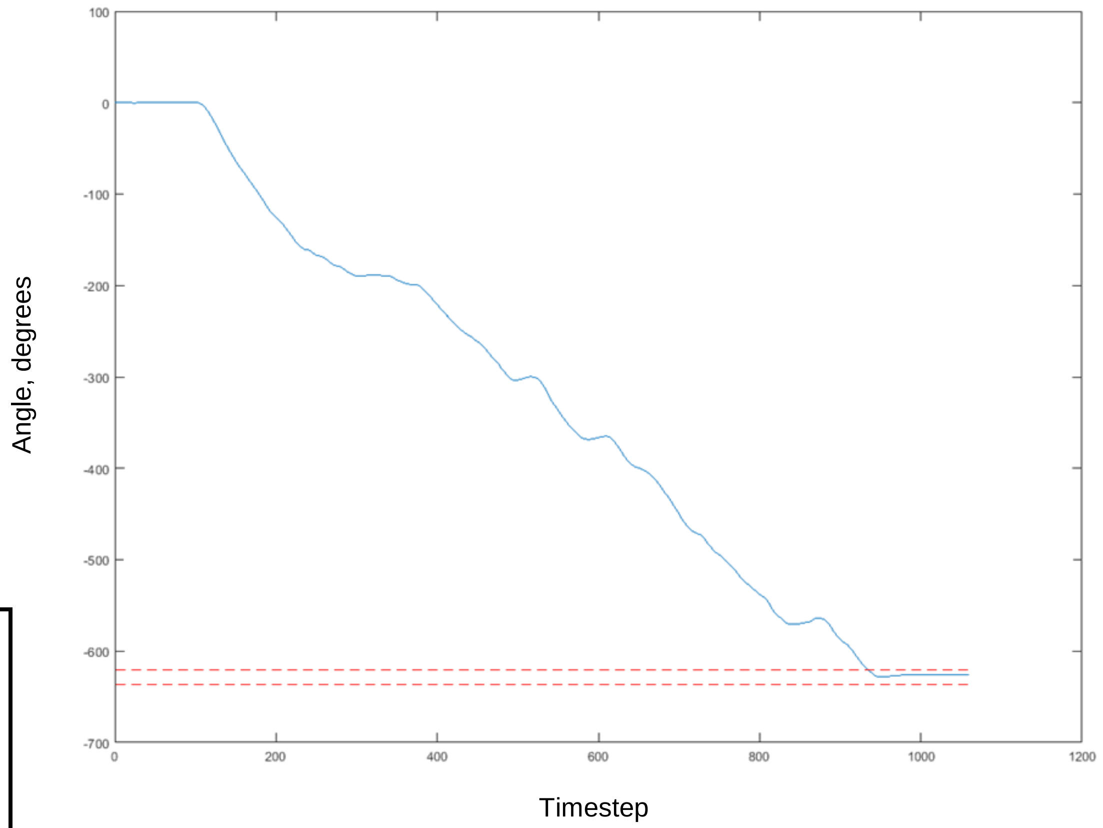
$$\mathbf{z} = (x, y, \varphi)^T$$



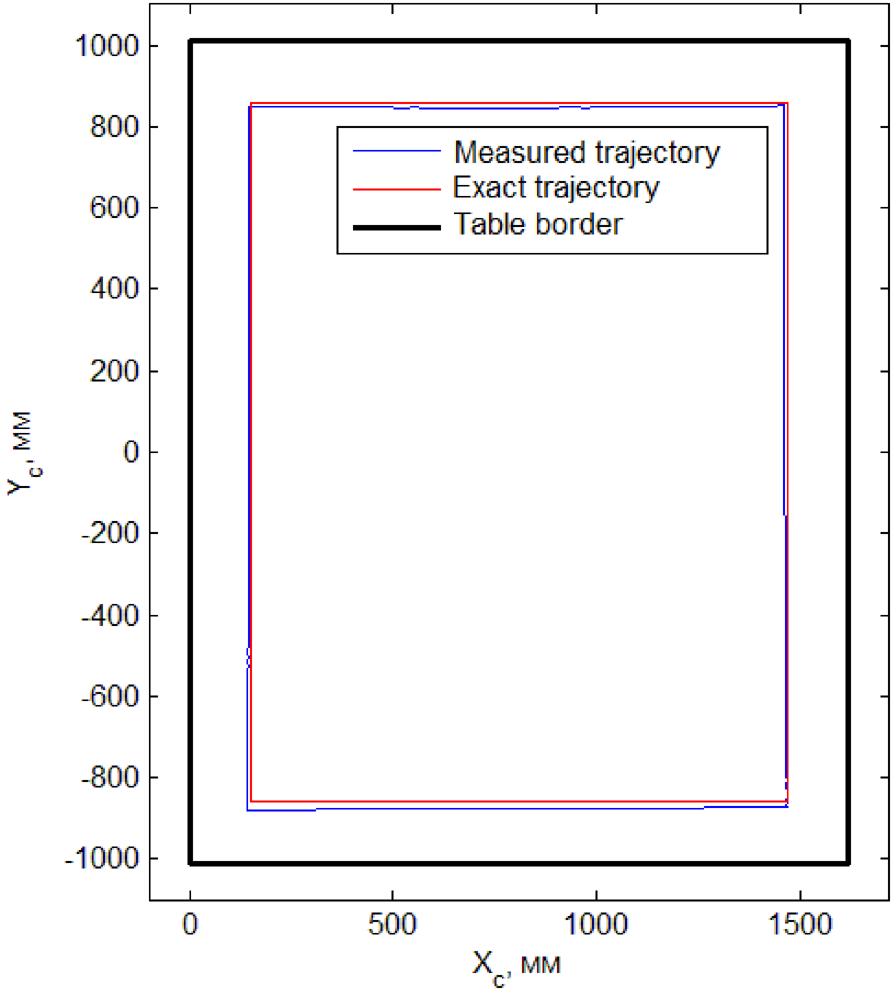
Experiment 1: Rolling motion

- The disk was rolled along the side of the stand
- The rotation angle matched the calculations

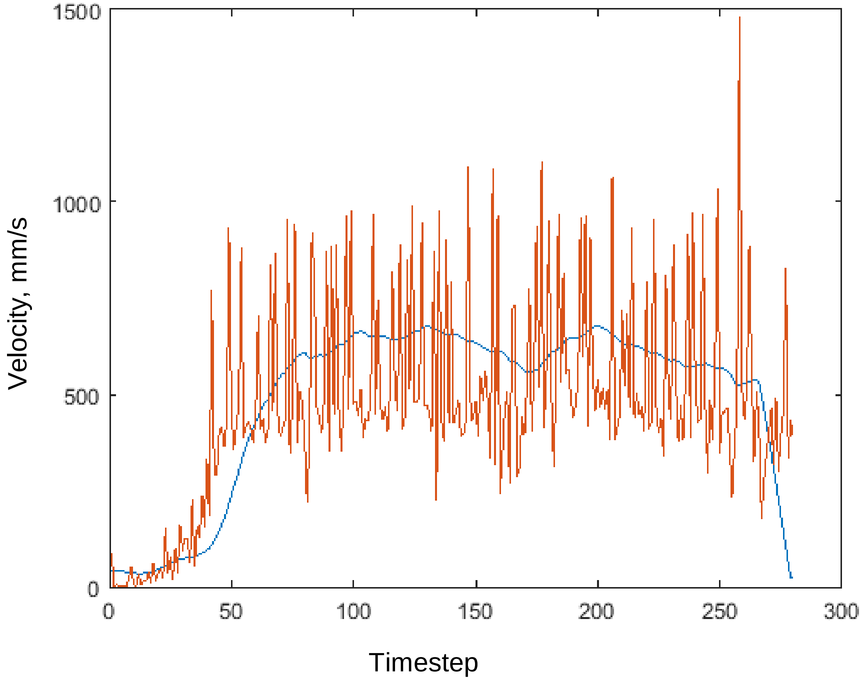


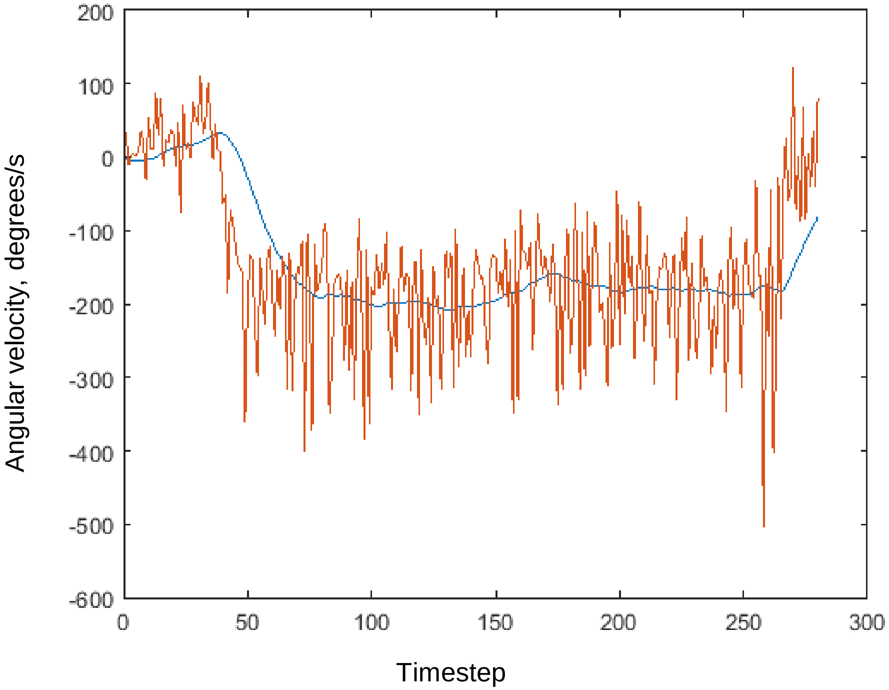


Experiment 2: Motion along the border



Experiment 3: Free motion





In red – velocity as a finite difference $$v = \frac{s_n - s_{n-1}}{\tau}$$

In blue – velocity obtained from Kalman filter

Conclusions

- Image processing is a powerful method that is used for satellite motion determination, including relative motion.
- Image processing steps:
  - Calibrate camera
  - Convert to binary image
  - Find all contours
  - Distinct required contours
  - Use filtering

Thank you for your attention