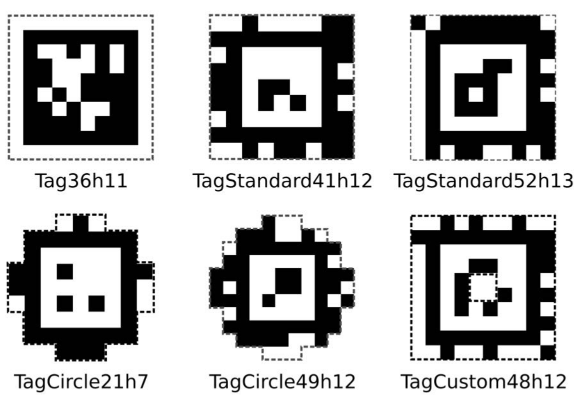
CSE276A - Visual Servoing

Henrik I Christensen

HW2 - Closing the loop with vision

- Due: 31 October @ midnight
- Two options:
  - Use AprilTags as landmarks in the environment
  - Use natural landmarks for extra credit (it is hard!)
    - Tutorial on how to use DL for detection of objects say Yolo
    - https://pyimagesearch.com/2018/11/12/yolo-object-detection-with-opencv/
    - 20% extra credit
- Use detected landmarks to estimate your own position
  - Correct for drift in the control of the vehicle

AprilTags

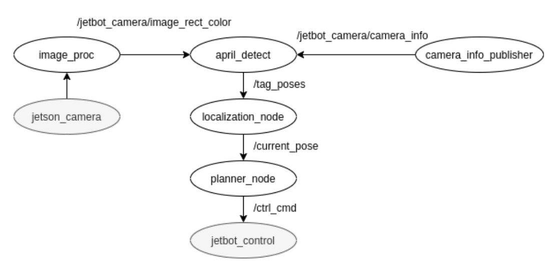


https://github.com/AprilRobotics/apriltag

Practical stuff

- You have to calibrate your camera !
- OpenCV see later
- ROS camera calibration

- Example process with ROS modules



Visual Servoing

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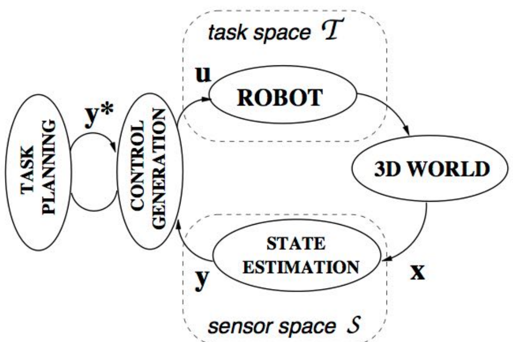
Literature

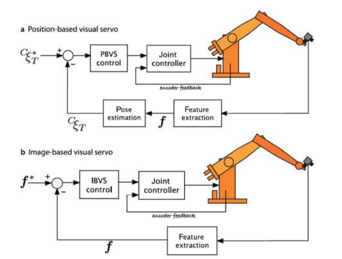
- Peter Corke, Robotics - Vision and Control, Springer Verlag, 2nd Edition, 2017 - Chapter 15

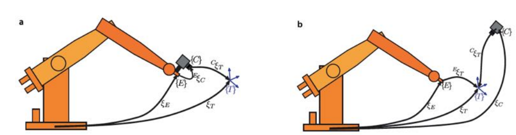
Major Robot Processes



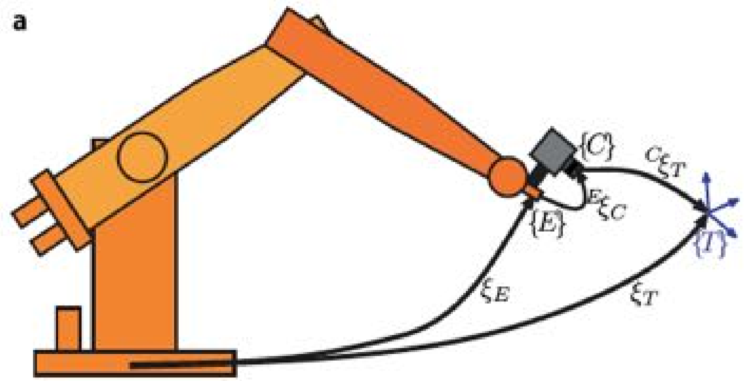
Types of visual serving

- Control Strategy
  - Position based servoing
  - Image based servoing
- Camera Placement
  - Eye-in-Hand
  - Stand-along

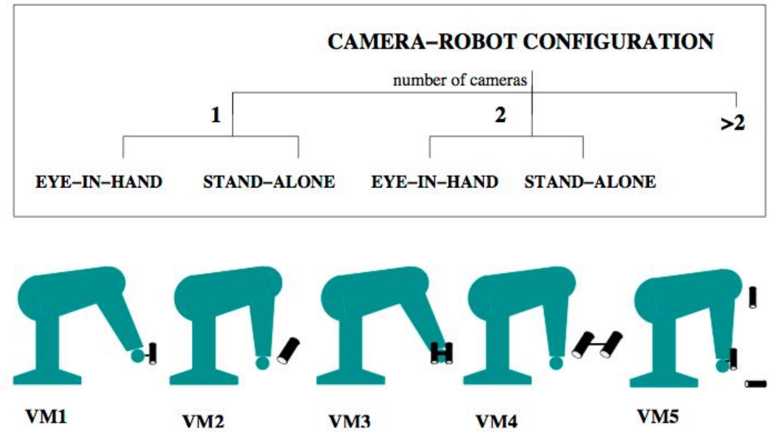




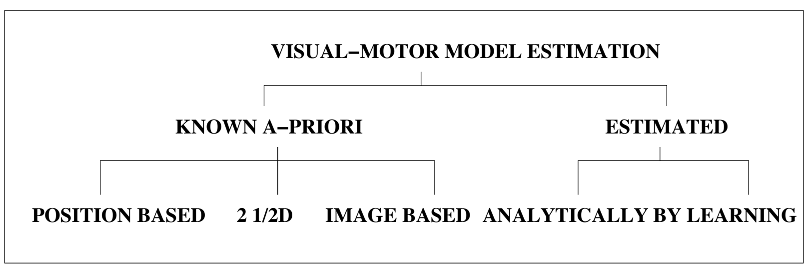
Process



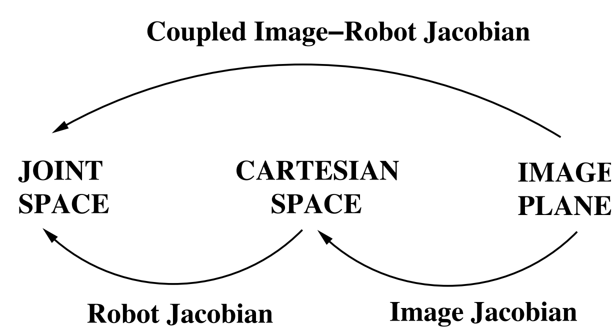
Categorization



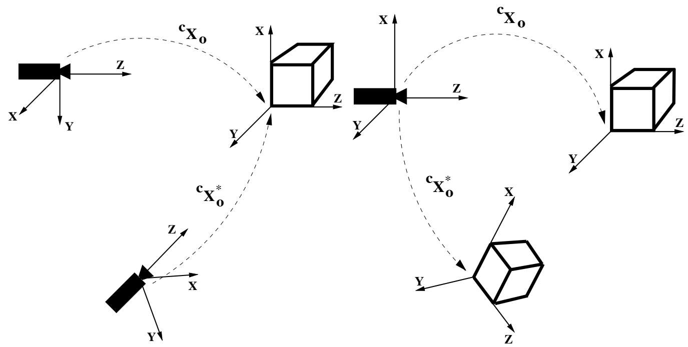
Visual Model Estimation



Utilization of kinematic models



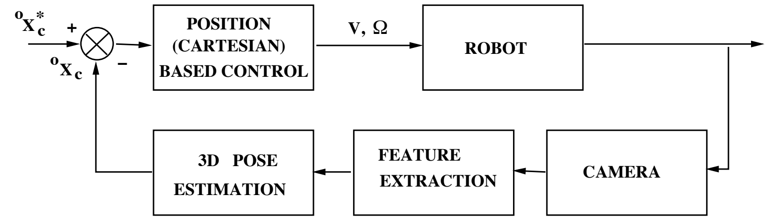
Example of position based visual servoing



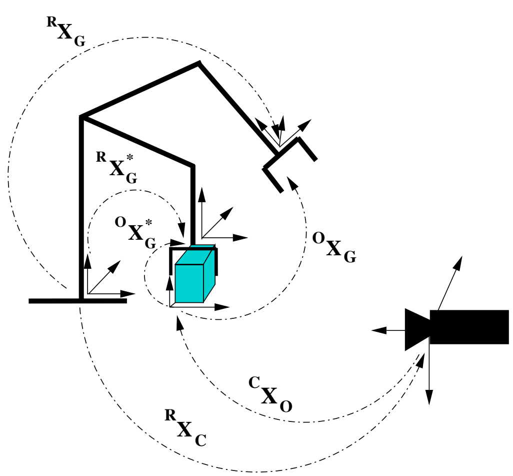
Moving Camera

Moving Object

Position based visual serving



Relevant reference frames



Control

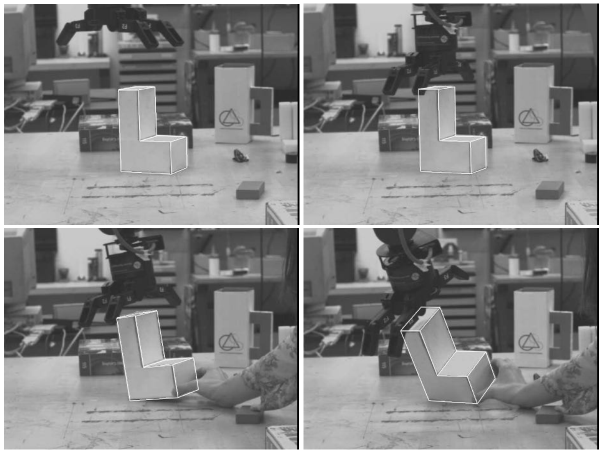
- Error Metric

$$\Delta\,{}^{R}\mathbf{t}_{G} = {}^{R}\mathbf{t}_{G} - {}^{R}\mathbf{t}_{G}^{*}$$
$$\Delta\,{}^{R}\theta_{G} = {}^{R}\theta_{G} - {}^{R}\theta_{G}^{*}$$

- Relevant Coordinate frames

$${}^{R}\mathbf{X}_{G}^{*} = {}^{R}\mathbf{X}_{C}\,{}^{C}\mathbf{X}_{O}\,{}^{O}\mathbf{X}_{G}^{*}$$

PBS Cartoon



Expanding the error metrics

- Expanding the transformation

$$ {}^R\mathbf{t}_G^* = {}^R\mathbf{R}_C\, {}^C\hat{\mathbf{R}}_O\, {}^O\mathbf{t}_G^* + {}^R\mathbf{R}_C\, {}^C\hat{\mathbf{t}}_O + {}^R\mathbf{t}_C $$
$$ {}^R\Omega_G^* = {}^R\Omega_C + {}^R\mathbf{R}_C\, {}^C\hat{\Omega}_O + {}^R\mathbf{R}_C\, {}^C\hat{\mathbf{R}}_O\, {}^O\Omega_G^* $$

- Integrating

$$ {}^R\theta_G^* \approx {}^R\theta_C + {}^R\mathbf{R}_C\, {}^C\hat{\theta}_O + {}^R\mathbf{R}_C\, {}^C\hat{\mathbf{R}}_O\, {}^O\theta_G^* $$

- Substituting from above

$$ \Delta\, {}^R\mathbf{t}_G = {}^R\mathbf{t}_G - {}^R\mathbf{t}_C - {}^R\mathbf{R}_C\, {}^C\hat{\mathbf{t}}_O - {}^R\mathbf{R}_C\, {}^C\hat{\mathbf{R}}_O\, {}^O\mathbf{t}_G^* $$
$$ \Delta\, {}^R\theta_G \approx {}^R\theta_G - {}^R\theta_C - {}^R\mathbf{R}_C\, {}^C\hat{\theta}_O - {}^R\mathbf{R}_C\, {}^C\hat{\mathbf{R}}_O\, {}^O\theta_G^* $$

Strategy

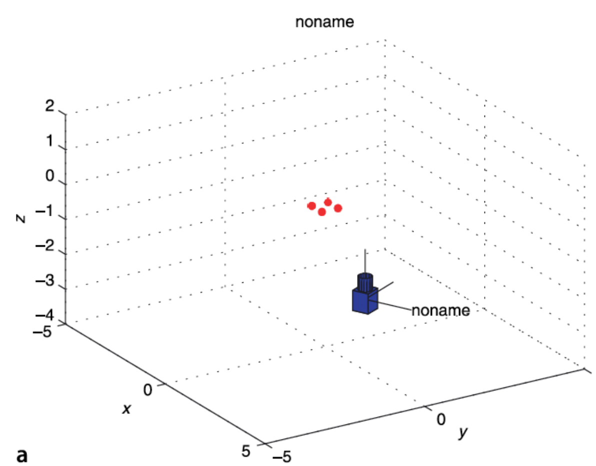
- Compute

$$ \mathbf{e} = \begin{bmatrix} \Delta\, {}^R\mathbf{t}_G \\ \Delta\, {}^R\theta_G \end{bmatrix} $$

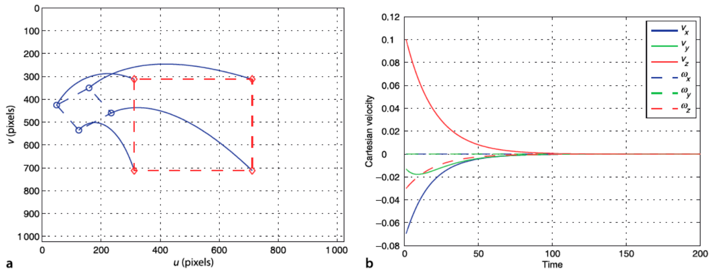
- The change in robot coordinates (use, PID, …)

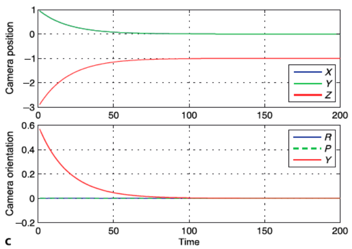
$$ \dot{\mathbf{q}} \approx \mathbf{K}\mathbf{e} $$

Simulated camera



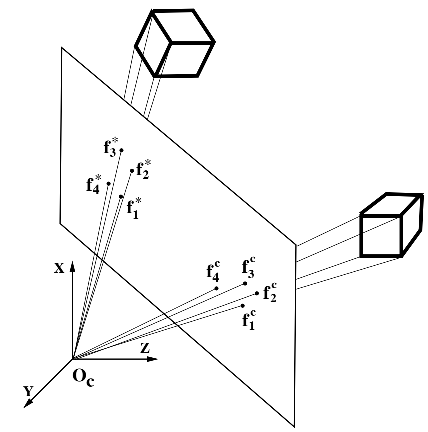
Example PBS simulation



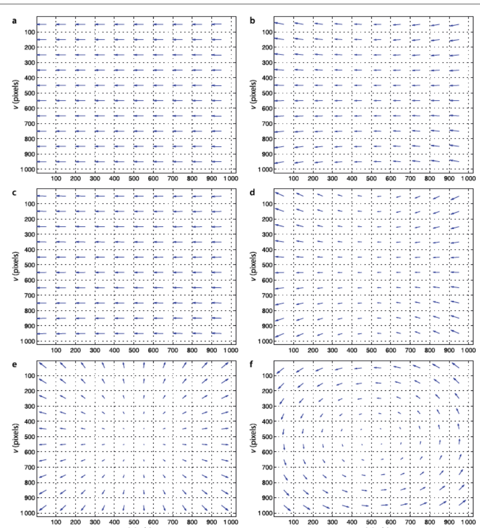



```
>> pbvs = PBVS(cam, 'T0', Tc0, 'Tf', TcStar_t)
Visual servo object: camera=noname
  200 iterations, 0 history
  P= -0.25      -0.25       0.25       0.25
      -0.25       0.25       0.25      -0.25
          0          0          0          0
  Tc0:   t = ( 1 1 -3), R = ( 34.3775deg |  0 0 1)
  Tc*_t: t = ( 0 0 1), R = nil
>> pbvs.run();
>> pbvs.plot_p();
>> pbvs.plot_vel();
>> pbvs.plot_camera();
```

Image Based Visual Servoing (IBVS)



Canonical image motion patterns



The Image Jacobian

- How does features move when we move the robot?

$$\dot{\mathbf{f}} = \mathbf{J}\,\dot{\mathbf{q}}$$

- Image Jacobian

$$J(\mathbf{q}) = \left[\ \frac{\delta \mathbf{f}}{\delta \mathbf{q}}\ \right] = \begin{bmatrix} \frac{\delta f_1(\mathbf{q})}{\delta q_1} & \cdots & \frac{\delta f_1(\mathbf{q})}{\delta q_m} \\ \vdots & \ddots & \vdots \\ \frac{\delta f_k(\mathbf{q})}{\delta q_1} & \cdots & \frac{\delta f_k(\mathbf{q})}{\delta q_m} \end{bmatrix}$$

Going back to basics

$$x = \frac{X}{Z},\ y = \frac{Y}{Z}$$

$$\dot{x} = \frac{\dot{X}Z - X\dot{Z}}{Z^2},\ \dot{y} = \frac{\dot{Y}Z - Y\dot{Z}}{Z^2}$$

$$\dot{\boldsymbol{P}} = -\boldsymbol{\omega} \times \boldsymbol{P} - \boldsymbol{v}$$

$$\begin{aligned} \dot{X} &= Y\omega_z - Z\omega_y - v_x \\ \dot{Y} &= Z\omega_x - X\omega_z - v_y \\ \dot{Z} &= X\omega_y - Y\omega_x - v_z \end{aligned}$$

Going back to basics

- With a unit focal length we would have

$$^C\dot{\mathbf{P}} = {}^C\Omega \times {}^C\mathbf{P} + {}^C\mathbf{V}$$

$$\begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} k_u & 0 \\ 0 & k_v \end{bmatrix} \begin{bmatrix} \frac{1}{Z} & 0 & -\frac{x}{Z} & -xy & 1+x^2 & -y \\ 0 & \frac{1}{Z} & -\frac{y}{Z} & -1-y^2 & xy & x \end{bmatrix} \begin{bmatrix} V_X \\ V_Y \\ V_Z \\ \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix}$$

- We can define an error metric

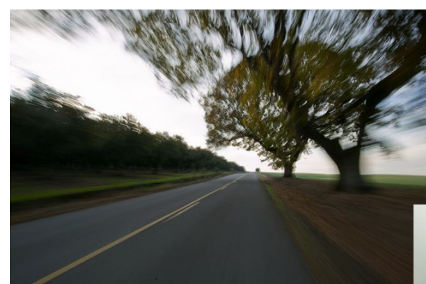
$$\mathbf{e}(\mathbf{f}) = \mathbf{f}^c - \mathbf{f}^*$$

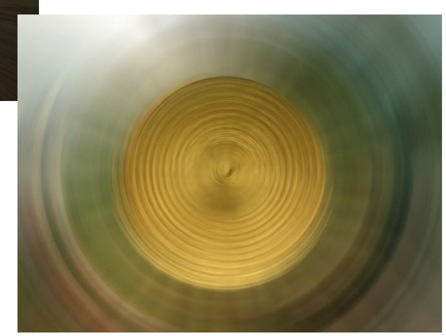
$$\mathbf{u} = \dot{\mathbf{q}} = \mathbf{K}\mathbf{J}^{\dagger}\mathbf{e}(\mathbf{f})$$

For K points we can stack

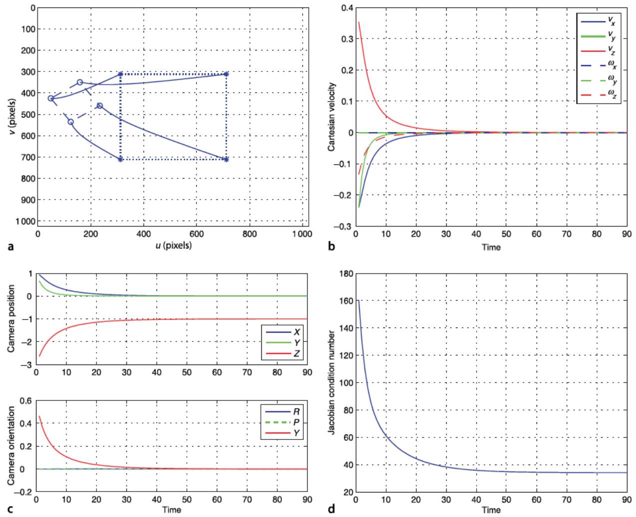
$$\begin{bmatrix} \dot{u}_1 \\ \dot{v}_1 \\ \vdots \\ \dot{u}_k \\ \dot{v}_k \end{bmatrix} = \mathbf{A} \begin{bmatrix} \frac{1}{Z_1} & 0 & -\frac{x_1}{Z_1} & -x_1y_1 & 1+x_1^2 & -y_1 \\ 0 & \frac{1}{Z_1} & -\frac{y_1}{Z_1} & -1-y_1^2 & x_1y_1 & x_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{1}{Z_k} & 0 & -\frac{x_k}{Z_k} & -x_ky_k & 1+x_k^2 & -y_k \\ 0 & \frac{1}{Z_k} & -\frac{y_k}{Z_k} & -1-y_k^2 & x_ky_k & x_k \end{bmatrix} \begin{bmatrix} V_X \\ V_Y \\ V_Z \\ \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix}$$

Visual impression of image jacobian

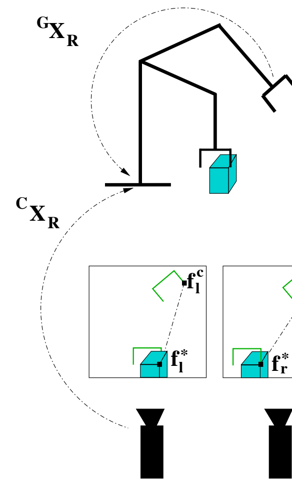




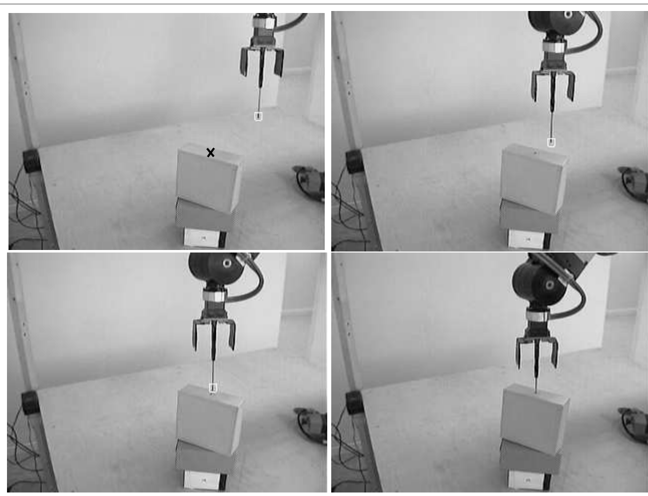
Simulated example



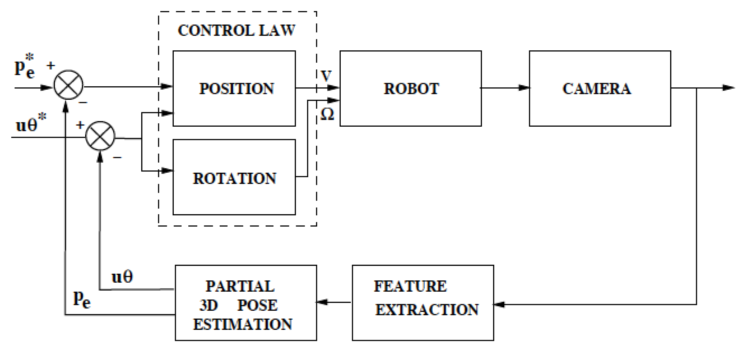
Sketch of an IBVS example



IBVS Cartoon



2.5D image based servoing



What if we could estimate Z online?

$$\begin{pmatrix}\dot{u}\\ \dot{v}\end{pmatrix} = \left(\begin{array}{ccc|ccc} -\frac{f}{\rho_u Z} & 0 & \frac{\bar{u}}{Z} & \frac{\rho_u \bar{u}\bar{v}}{f} & -\frac{f^2+\rho_u^2\bar{u}^2}{\rho_u f} & \bar{v} \\ 0 & -\frac{f}{\rho_v Z} & \frac{\bar{v}}{Z} & \frac{f^2+\rho_v^2\bar{v}^2}{\rho_v f} & -\frac{\rho_v \bar{u}\bar{v}}{f} & -\bar{u} \end{array}\right)\begin{pmatrix}\boldsymbol{v}\\ \omega\end{pmatrix}$$

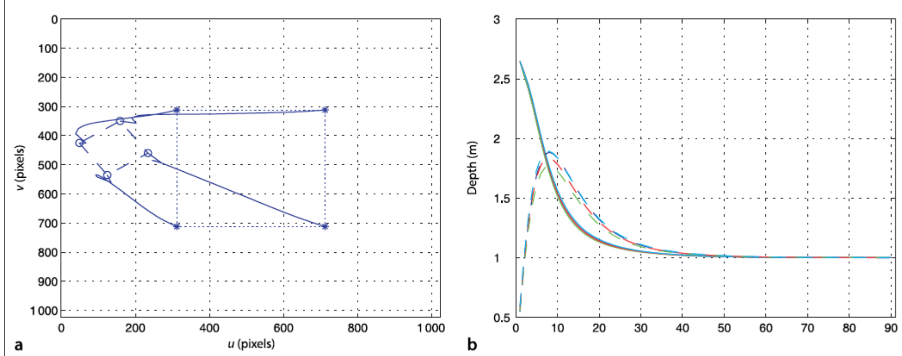
$$= \left(\tfrac{1}{Z}\boldsymbol{J}_t \;\middle|\; \boldsymbol{J}_\omega\right)\begin{pmatrix}\boldsymbol{v}\\ \omega\end{pmatrix}$$

$$= \frac{1}{Z}\boldsymbol{J}_t\boldsymbol{v} + \boldsymbol{J}_\omega \omega$$

- We can rearrange

$$(\boldsymbol{J}_t\boldsymbol{v})\frac{1}{Z} = \begin{pmatrix}\dot{u}\\ \dot{v}\end{pmatrix} - \boldsymbol{J}_\omega\omega \qquad => \qquad \mathbf{A}\boldsymbol{\theta} = \mathbf{b}$$

Example from the book



Summary / Take Home

- Image vs. position based servoing
- Derivation of motion impact on image coordinates
- Use of basic motion models to control the robot
- Great support for PBS and IBVS in the RVT toolkit