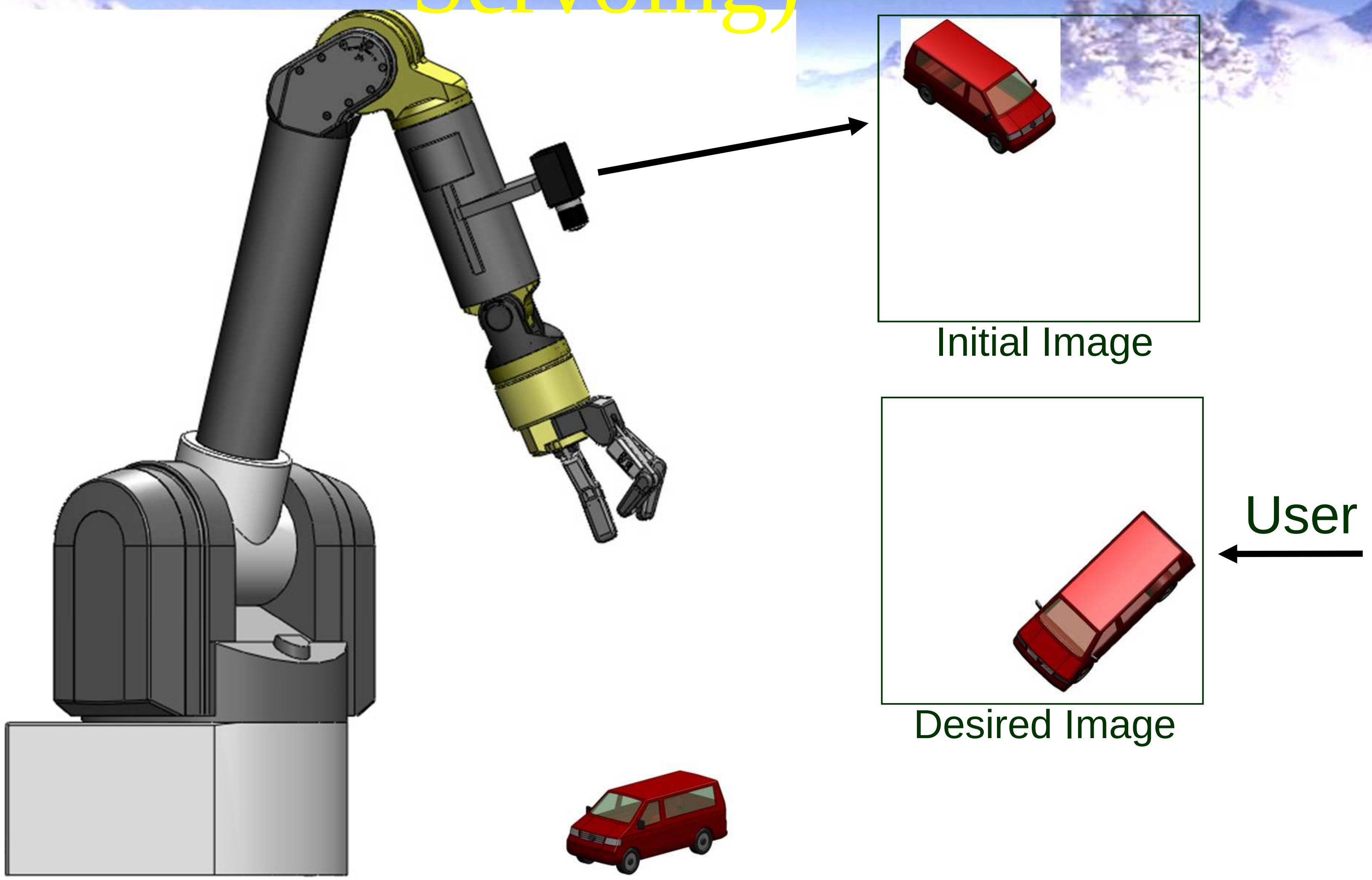
Robot Vision
Control of robot motion from video

M. Jagersand

Vision-Based Control (Visual Servoing)



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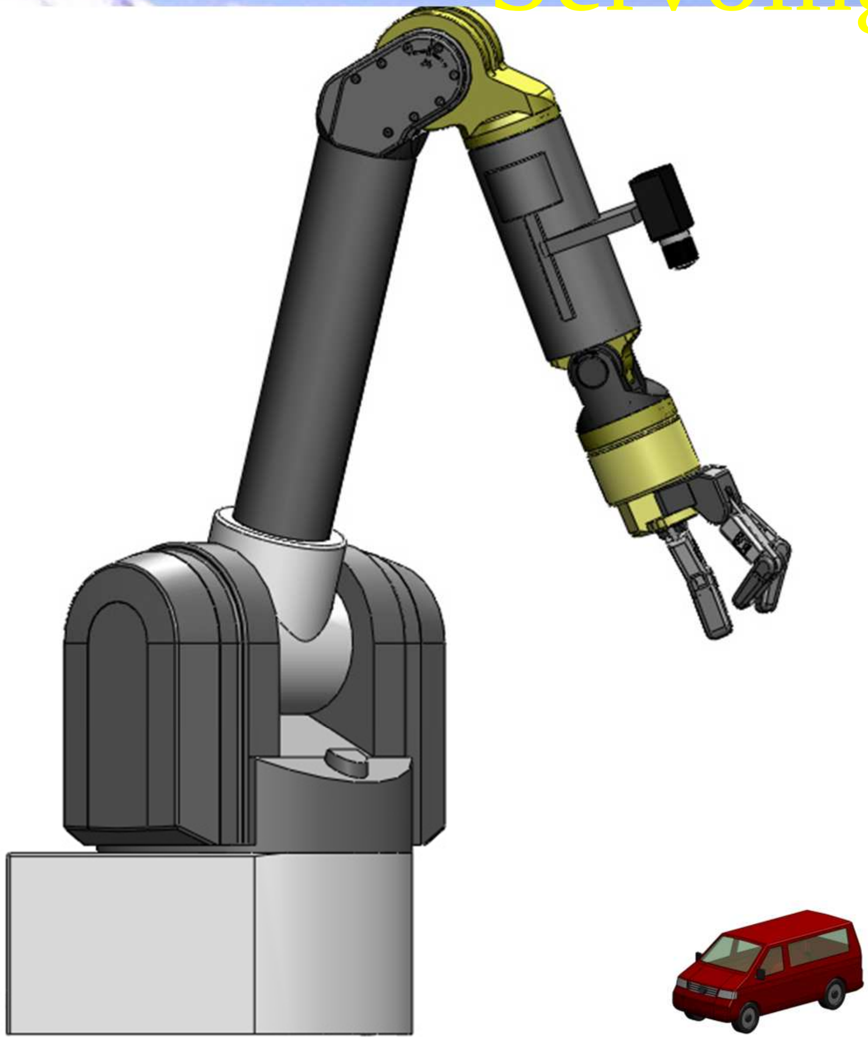

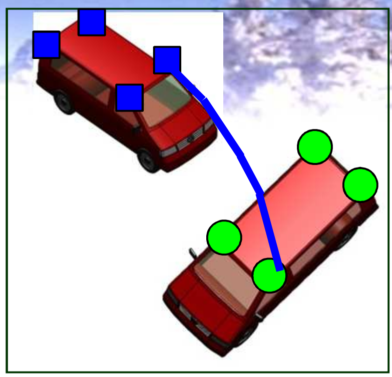

: Current Image Features
: Desired Image Features

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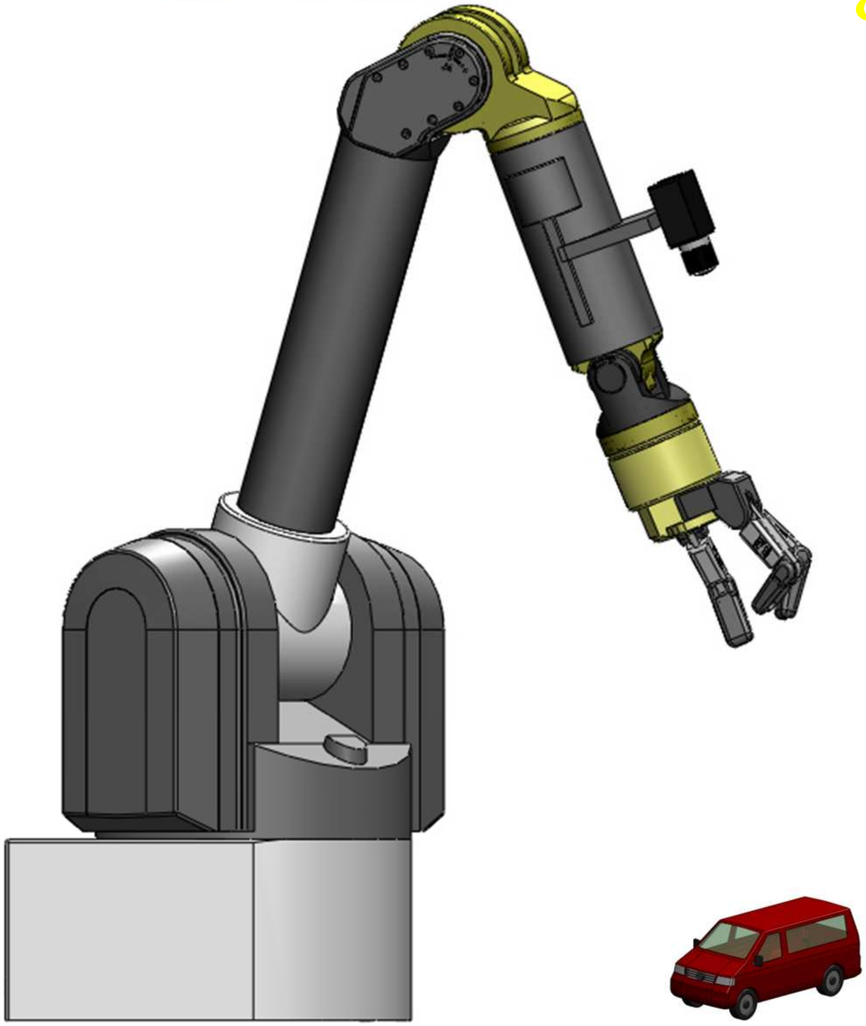
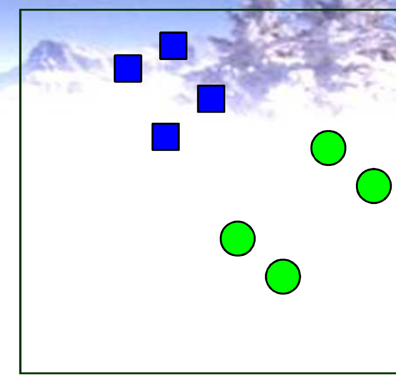
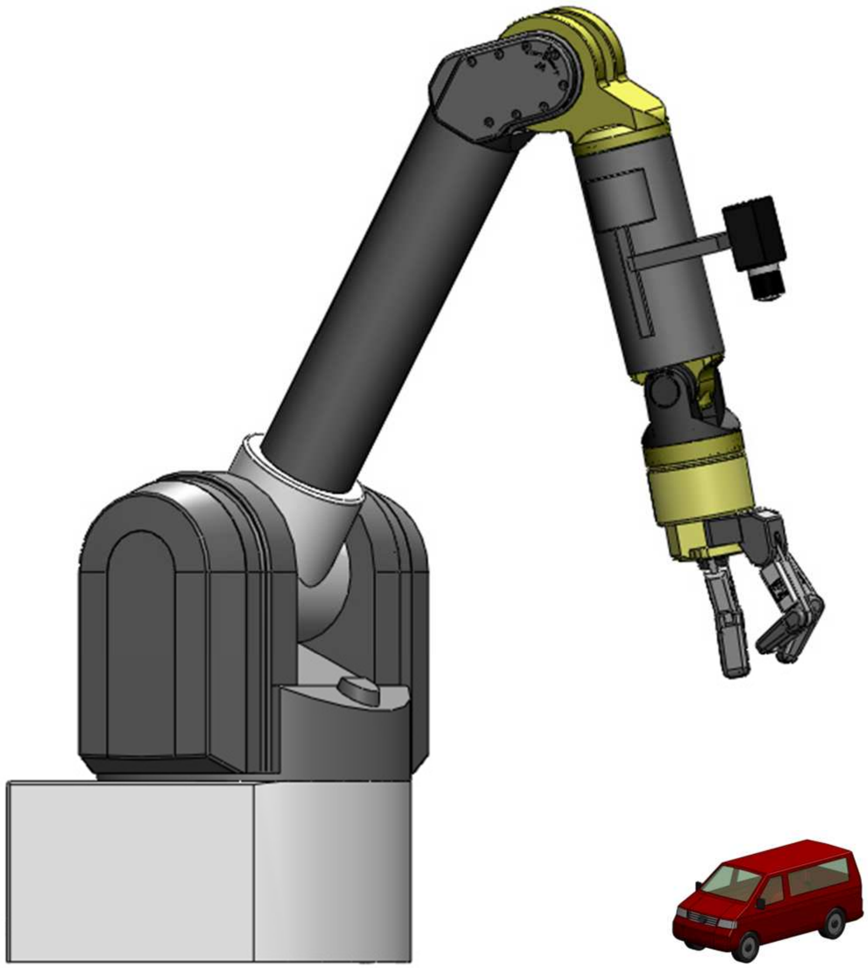


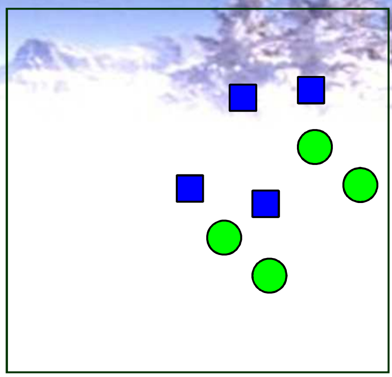


■ : Current Image Features

● : Desired Image Features

Vision-Based Control (Visual Servoing)





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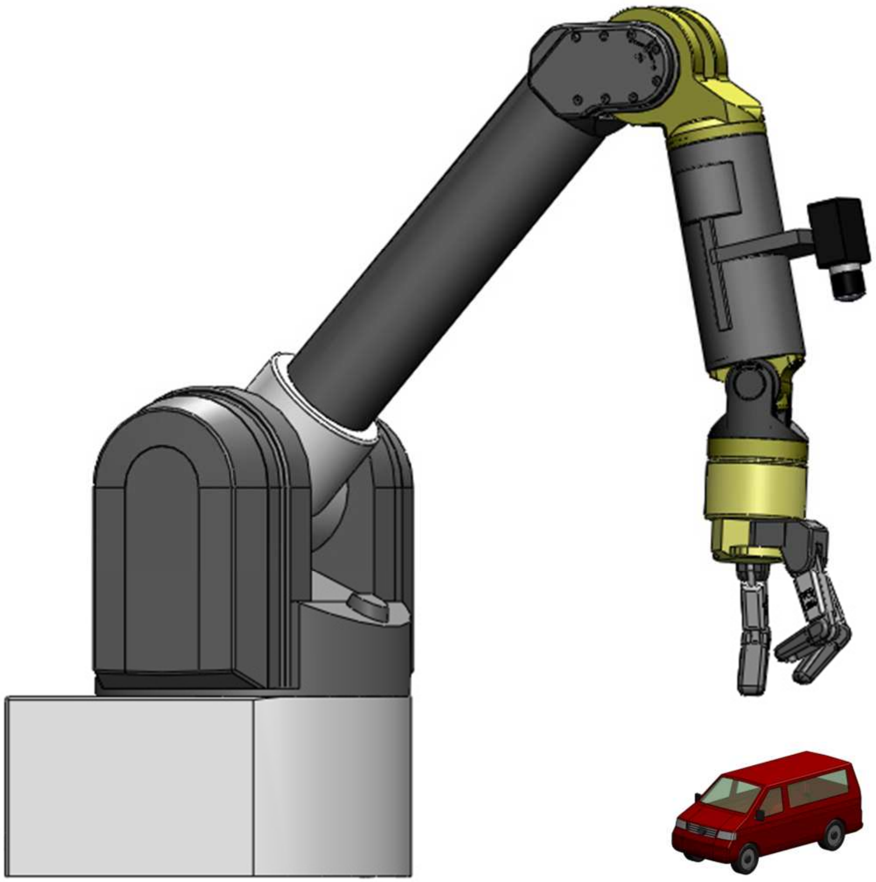
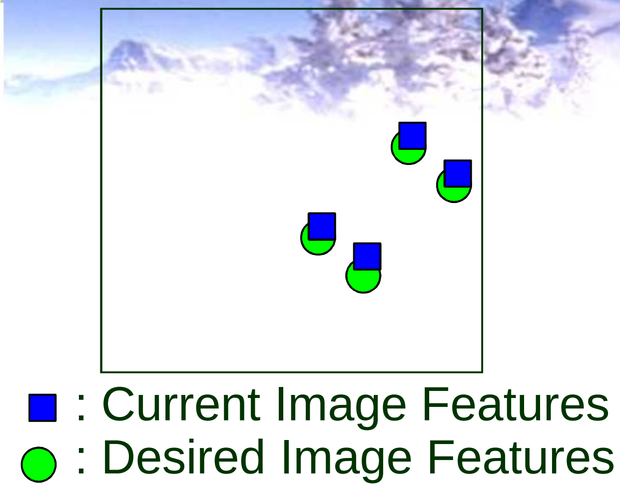
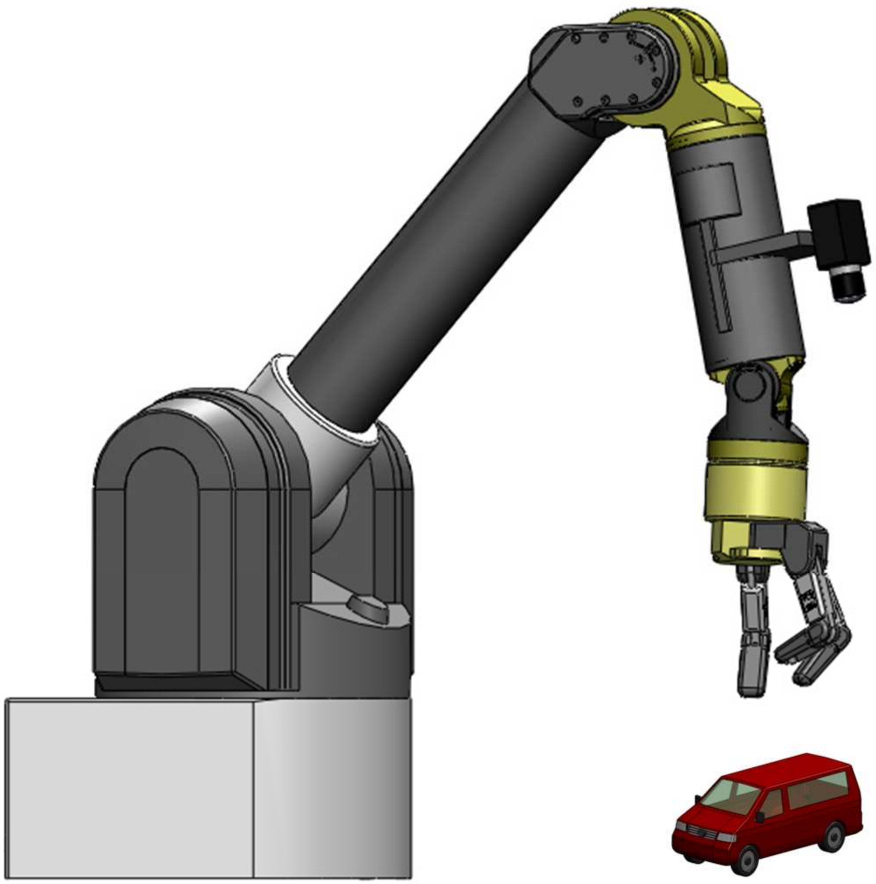
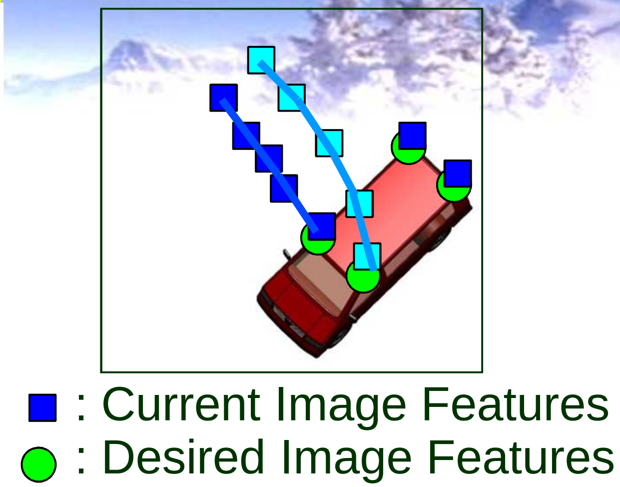


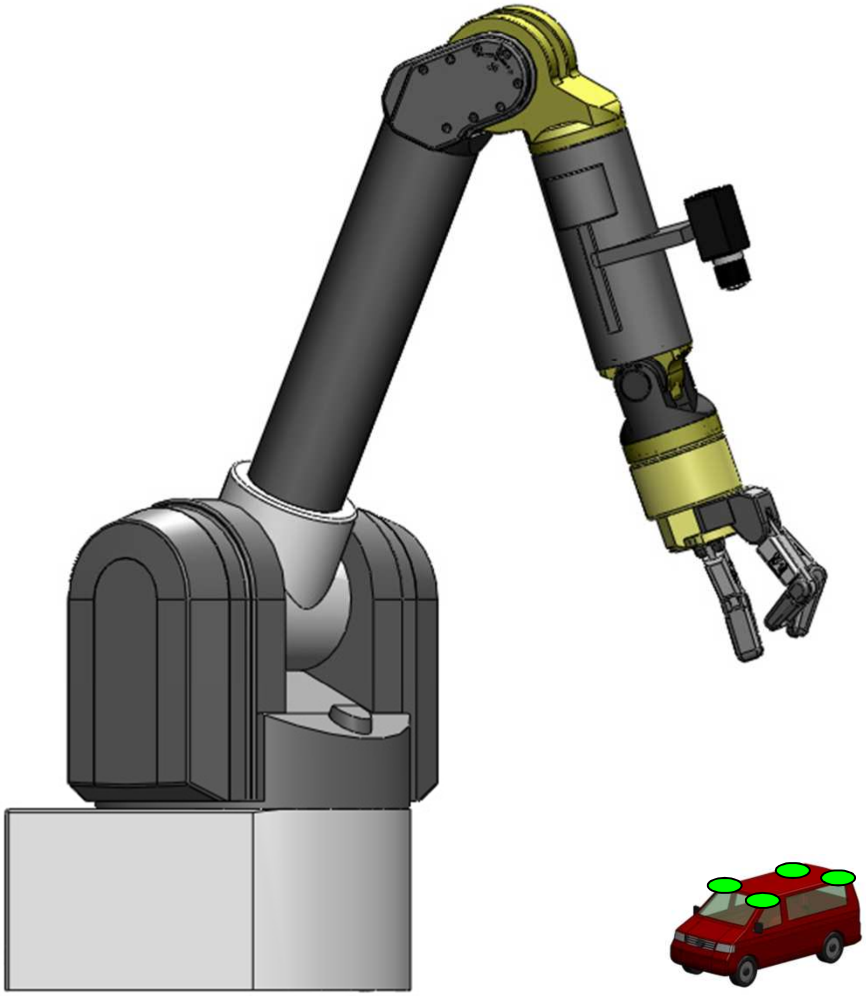


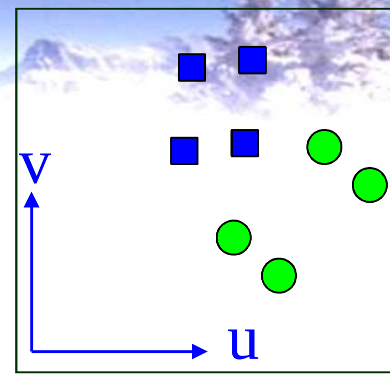
Vision-Based Control (Visual Servoing)





u,v Image-Space Error





■ : Current Image Features

● : Desired Image Features

$$\mathbf{E} = [\,●\; - \;■\,]$$

One point

$$\mathbf{E} = [\mathbf{y}_0 - \mathbf{y}^*]$$

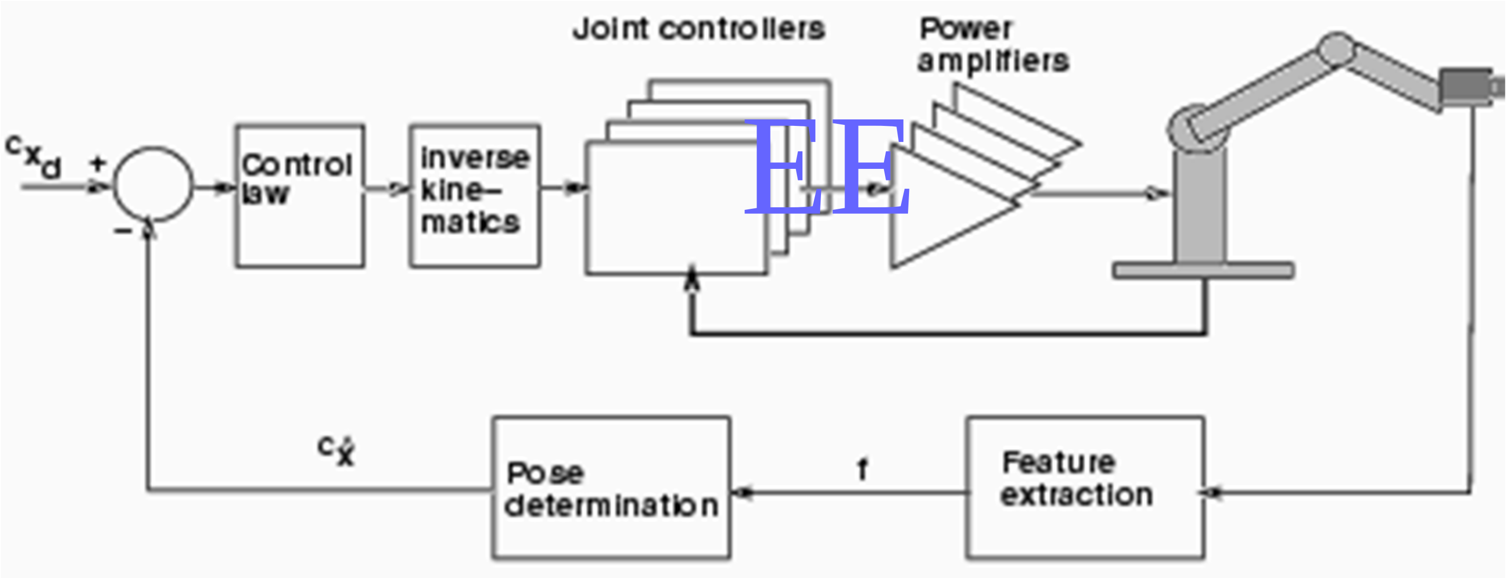
Pixel coord

$$\mathbf{E} = \begin{bmatrix} y_u \\ y_v \end{bmatrix} - \begin{bmatrix} y_u \\ y_v \end{bmatrix}^*$$

Many points

$$\mathbf{E} = \begin{bmatrix} y_1 \\ \vdots \\ y_{16} \end{bmatrix}^* - \begin{bmatrix} y_1 \\ \vdots \\ y_{16} \end{bmatrix}_0$$

Conventional Robotics: Motion command in base coord



- We focus on the geometric transforms

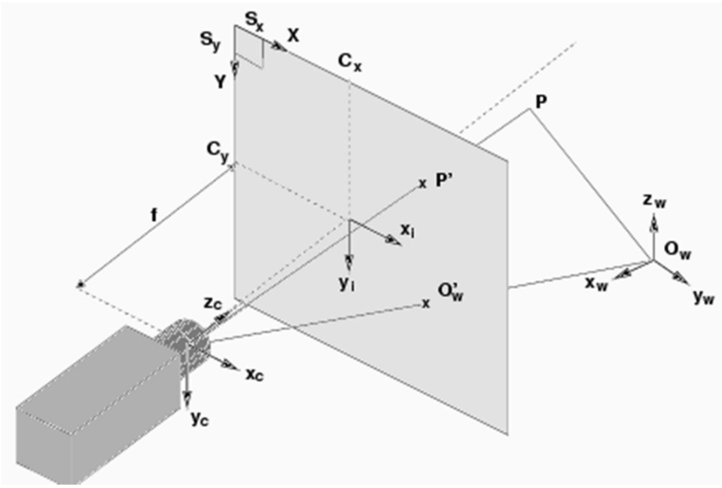
Problem: Lots of coordinate frames to calibrate

Camera

- Center of projection
- Different models

Robot

- Base frame
- End-effector frame
- Object



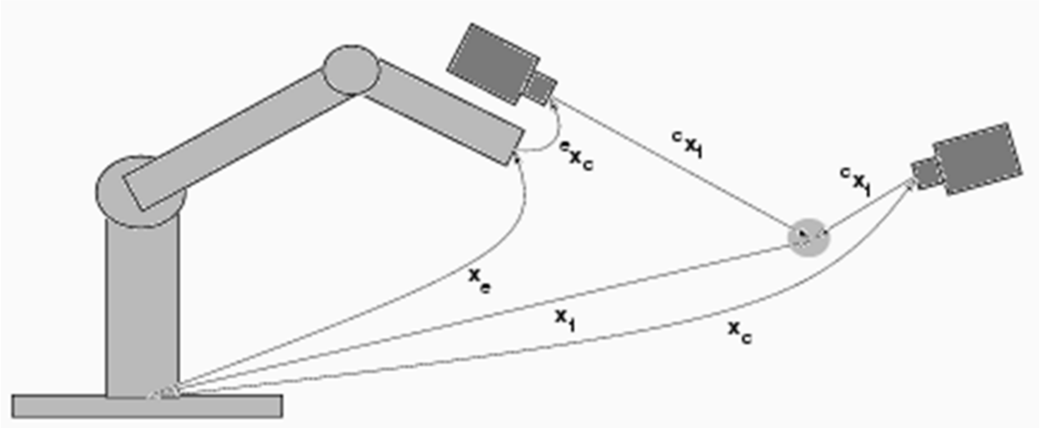
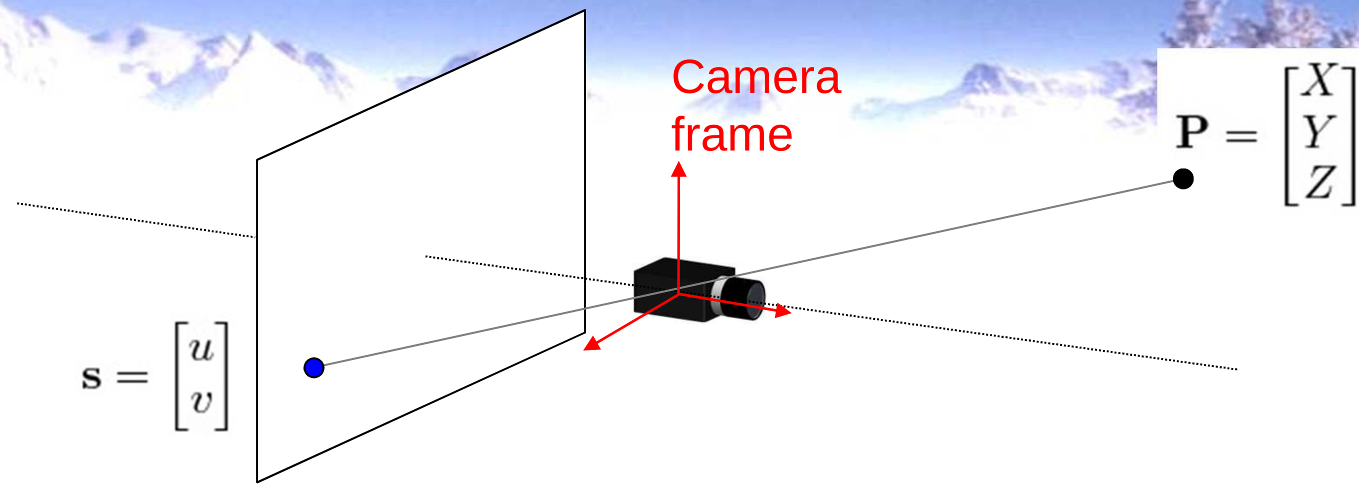


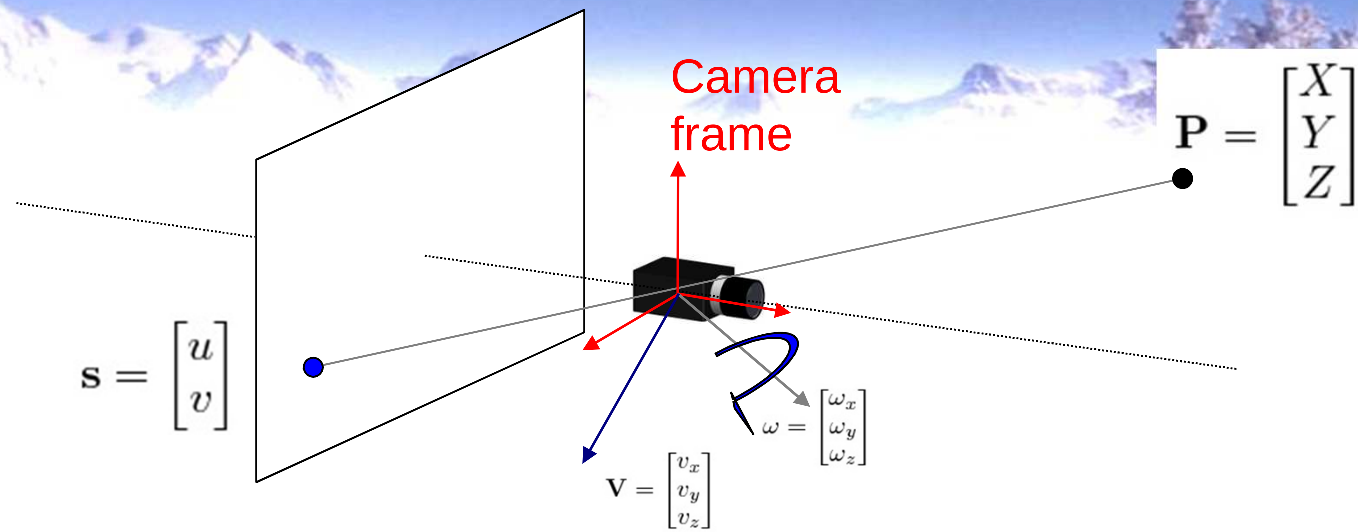
Image Formation is Nonlinear



$$u = f\frac{X}{Z}$$

$$v = f\frac{Y}{Z}$$

Camera Motion to Feature Motion



$$u = f\frac{X}{Z} \qquad v = f\frac{Y}{Z}$$

$$\begin{cases} \dot{u} = f\left(\dfrac{\dot{X}}{Z} - \dfrac{X\dot{Z}}{Z^2}\right) = f\dfrac{\dot{X}}{Z} - \dfrac{u\dot{Z}}{Z} \\ \dot{v} = f\left(\dfrac{\dot{Y}}{Z} - \dfrac{Y\dot{Z}}{Z^2}\right) = f\dfrac{\dot{Y}}{Z} - \dfrac{v\dot{Z}}{Z} \end{cases}$$

$$\mathbf{P} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\dot{\mathbf{P}} = -\mathbf{V} - \omega \times \mathbf{P}$$

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

Camera Motion to Feature Motion

$$\begin{cases} \dot{u} = f\dfrac{-v_x - \omega_y Z + \omega_z Y}{Z} - \dfrac{u(-v_z - \omega_x Y + \omega_y X)}{Z} \\ \dot{v} = f\dfrac{-v_y - \omega_z X + \omega_x Z}{Z} - \dfrac{v(-v_z - \omega_x Y + \omega_y X)}{Z} \end{cases}$$

$$\begin{cases} \dot{u} = -\dfrac{f}{Z}v_x + 0.v_y + \dfrac{u}{Z}v_z + \dfrac{uv}{f}\omega_x - (f + \dfrac{u^2}{f})\omega_y + v\omega_z \\ \dot{v} = 0.v_x - \dfrac{f}{Z}v_y + \dfrac{v}{Z}v_z + (f + \dfrac{v^2}{f})\omega_x - \dfrac{uv}{f}\omega_y - u\omega_z \end{cases}$$

$$\begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} -\frac{f}{Z} & 0 & \frac{u}{Z} & \frac{uv}{f} & -\frac{u^2+f^2}{f} & v \\ 0 & -\frac{f}{Z} & \frac{v}{Z} & \frac{v^2+f^2}{f} & -\frac{uv}{f} & -u \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

Interaction matrix is a Jacobian.

$$\dot{\mathbf{s}} = \mathbf{L}\begin{bmatrix} \mathbf{V} \\ \omega \end{bmatrix}$$

This derivation is for one point.

Q. How to extend to more points?

Q. How many points needed?

Problem: Lots of coordinate frames to calibrate

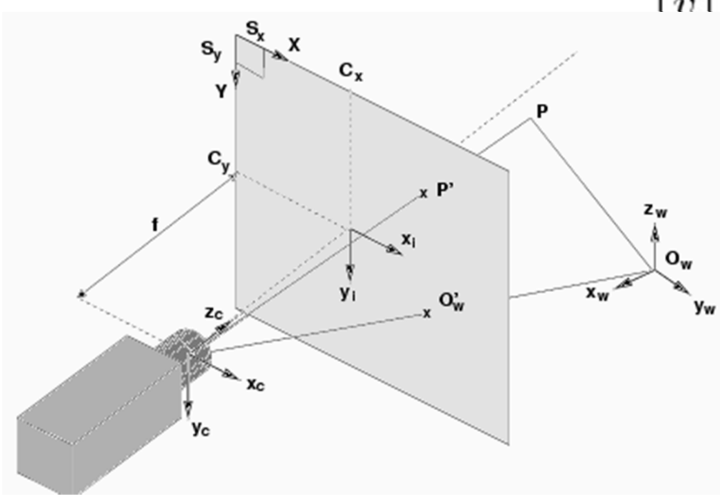
Camera

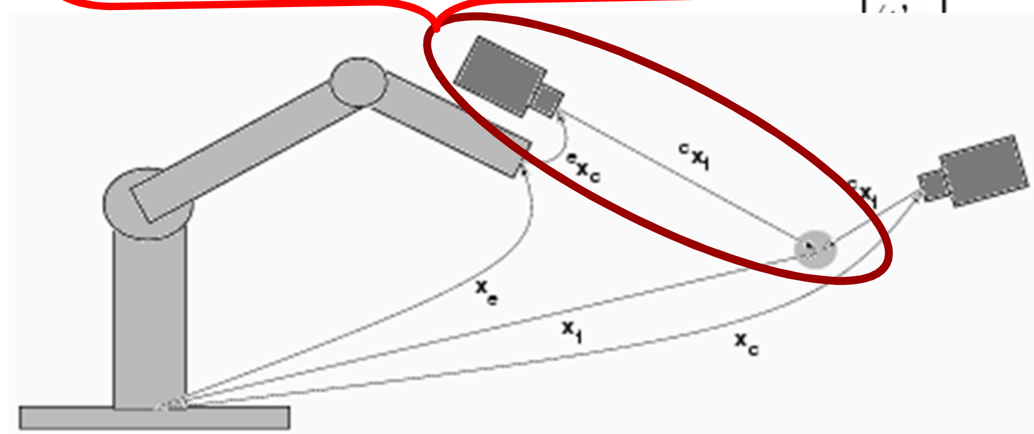
- Center of projection
- Different models

Robot

- Base frame
- End-effector frame
- Object

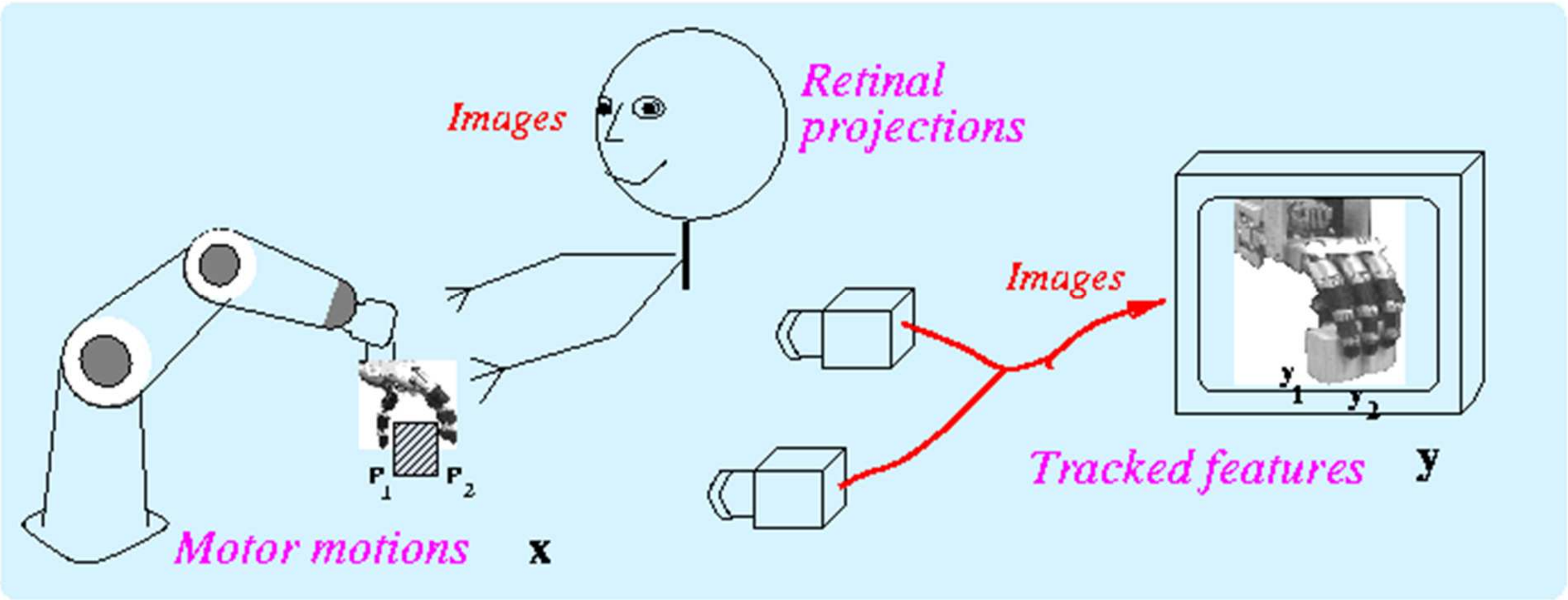
$$\begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} -\frac{f}{Z} & 0 & \frac{u}{Z} & \frac{uv}{f} & -\frac{u^2+f^2}{f} & v \\ 0 & -\frac{f}{Z} & \frac{v}{Z} & \frac{v^2+f^2}{f} & -\frac{uv}{f} & -u \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$





Only covered one transform!

Other (easier) solution: Image-based motion control



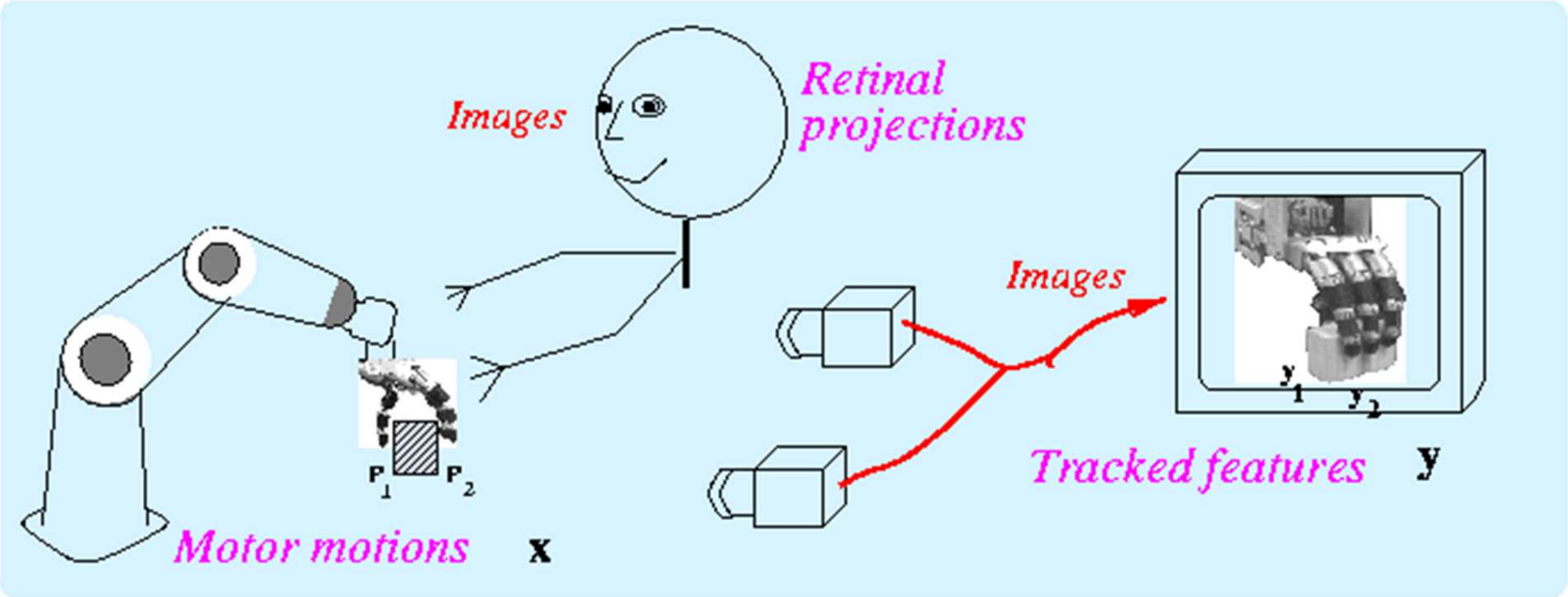
Motor-Visual function: y=f(x)

Achieving 3d tasks
via
2d image control

Other (easier) solution: Image-based motion control

Note: What follows will work for one or two (or 3..n) cameras.
Either fixed or on the robot.

Here we will use two cam



Motor-Visual function: y=f(x)

Achieving 3d tasks
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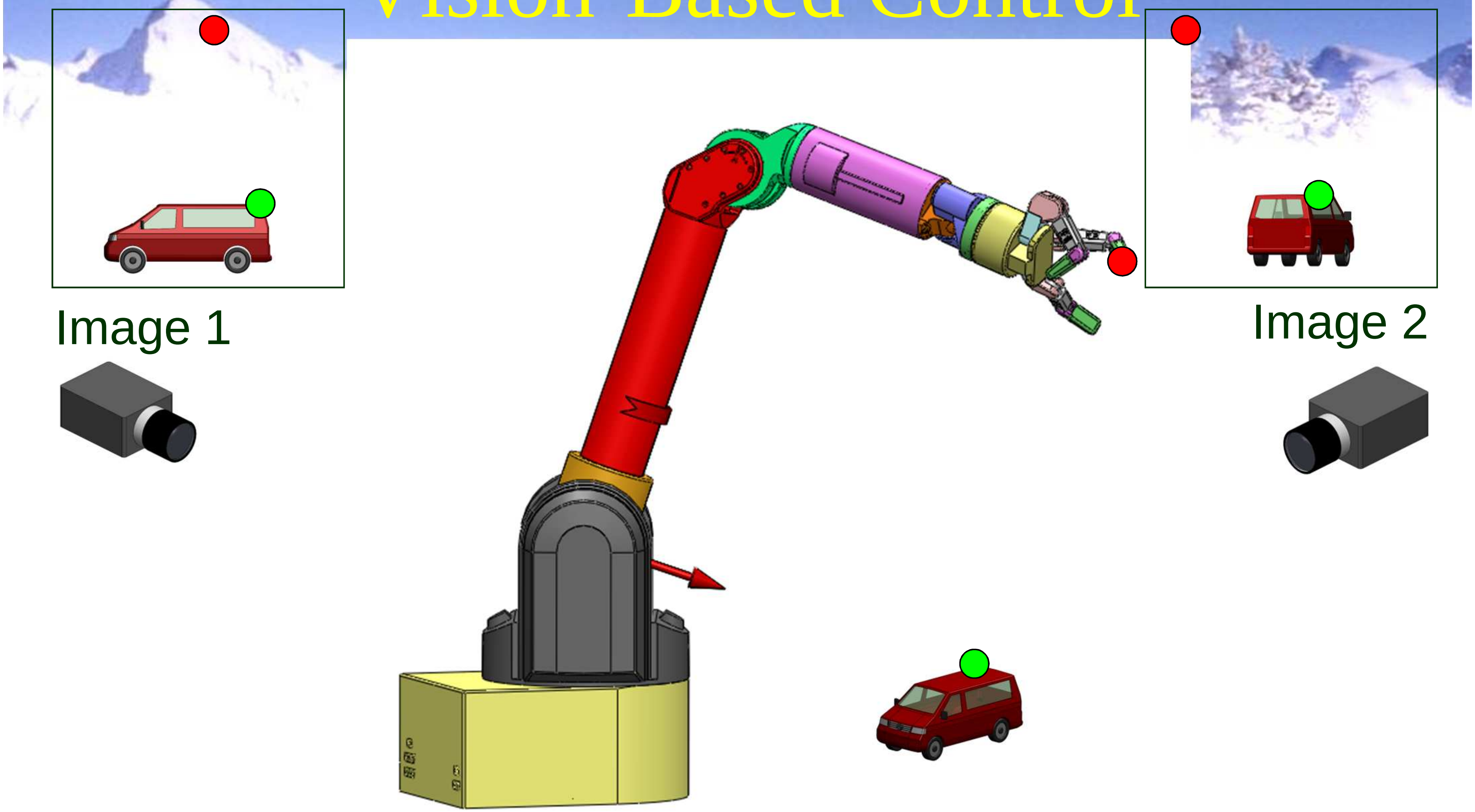
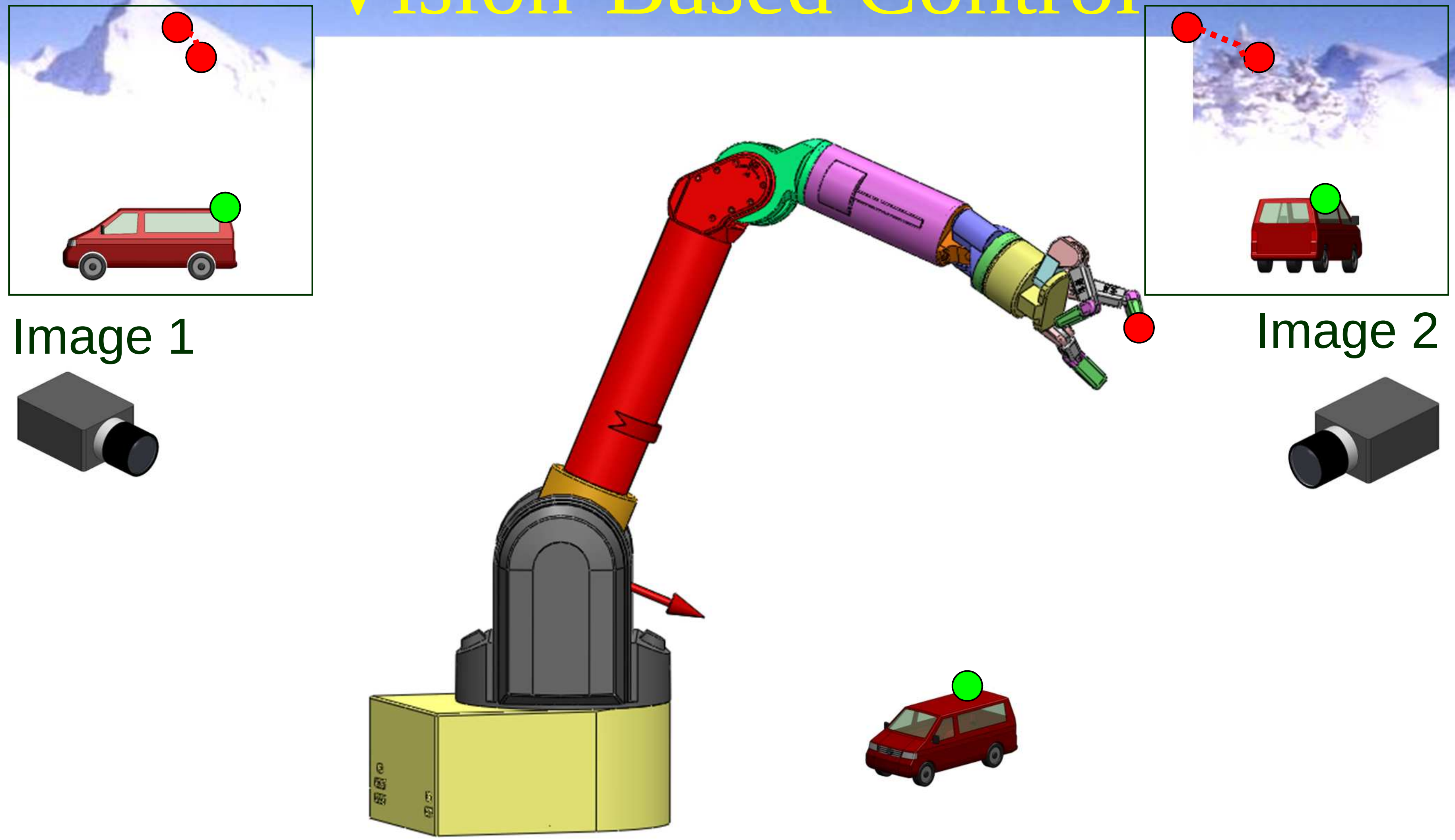
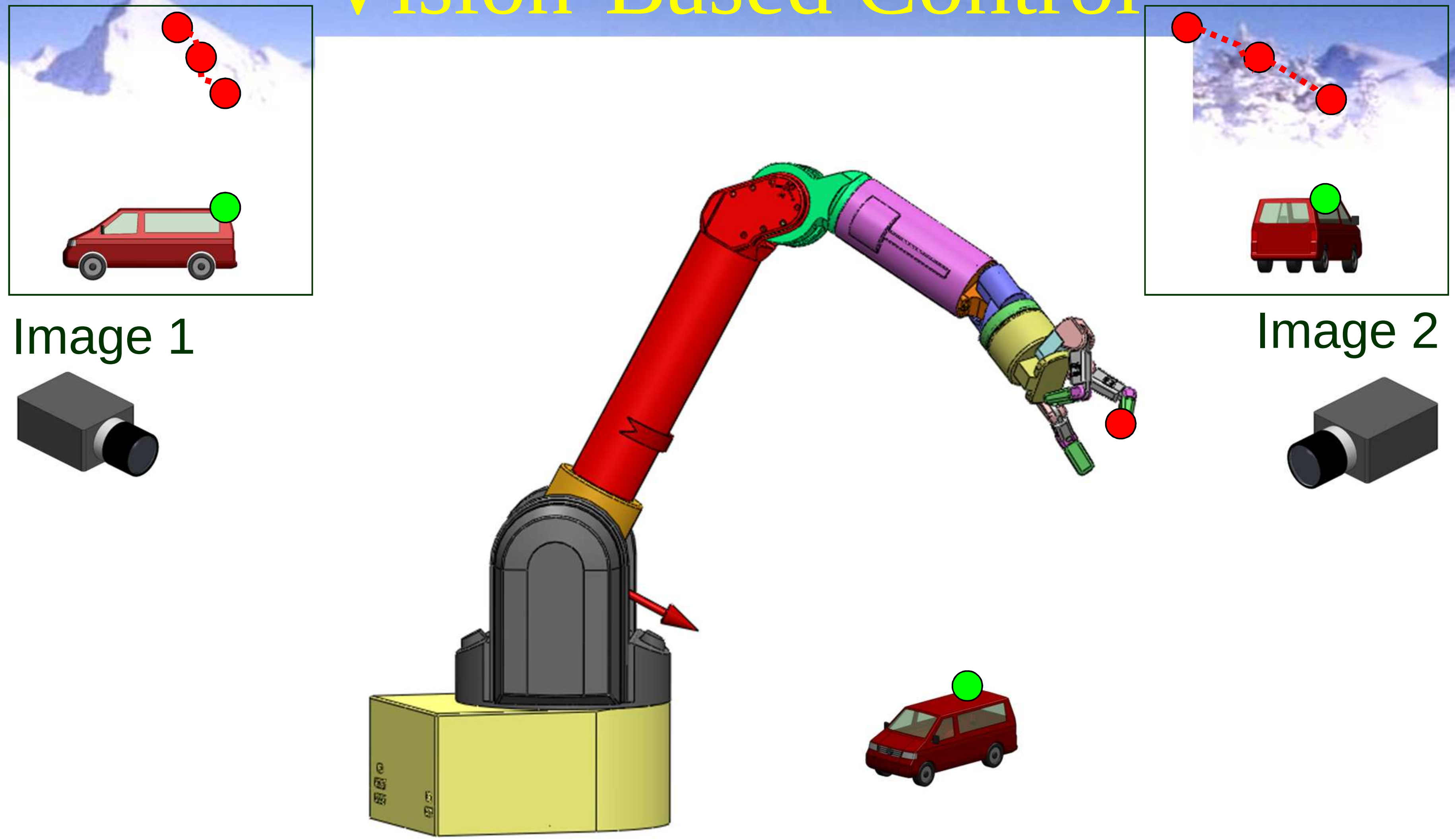
Vision-Based Control



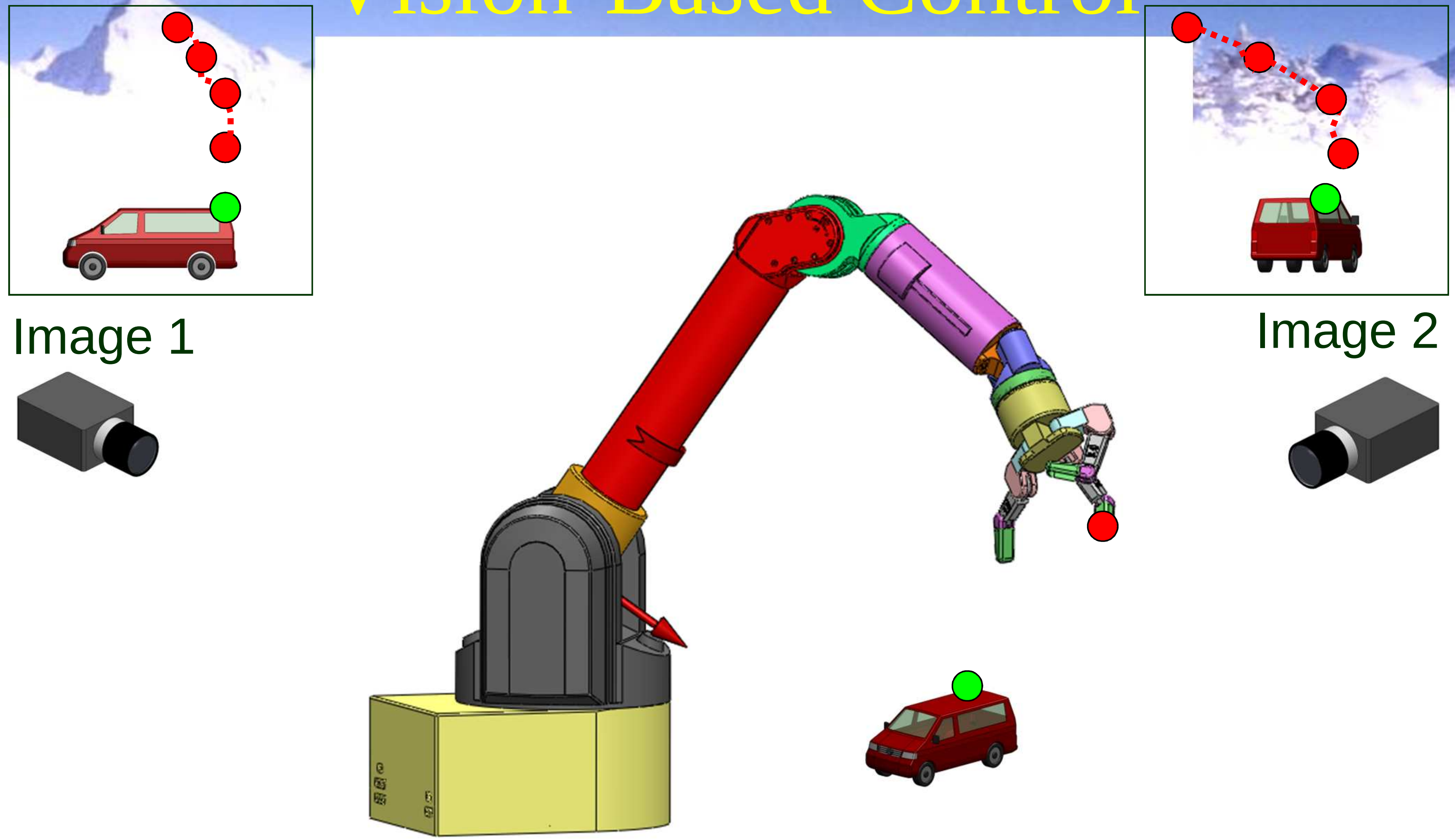
Vision-Based Control



Vision-Based Control



Vision-Based Control



Vision-Based Control

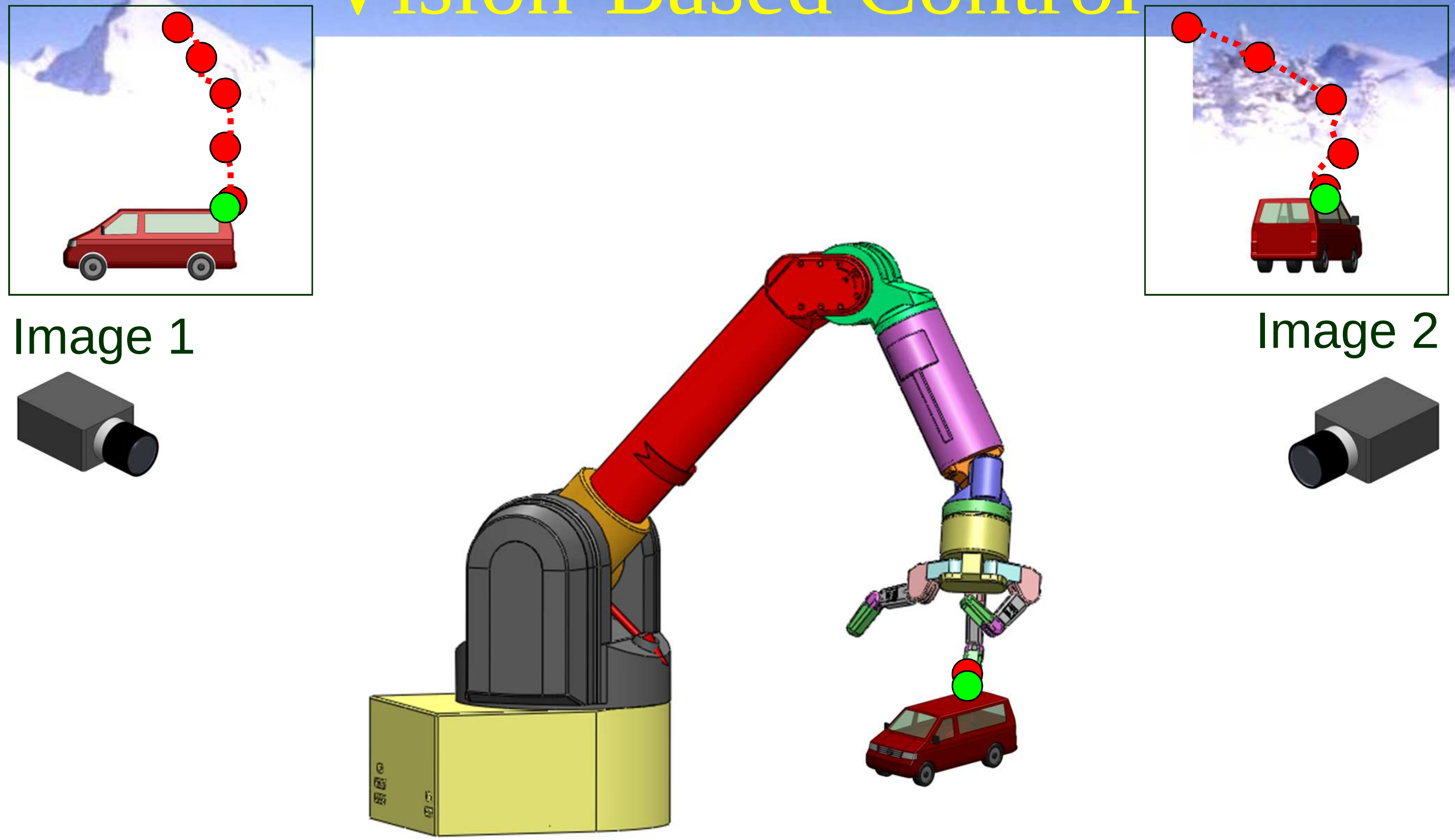
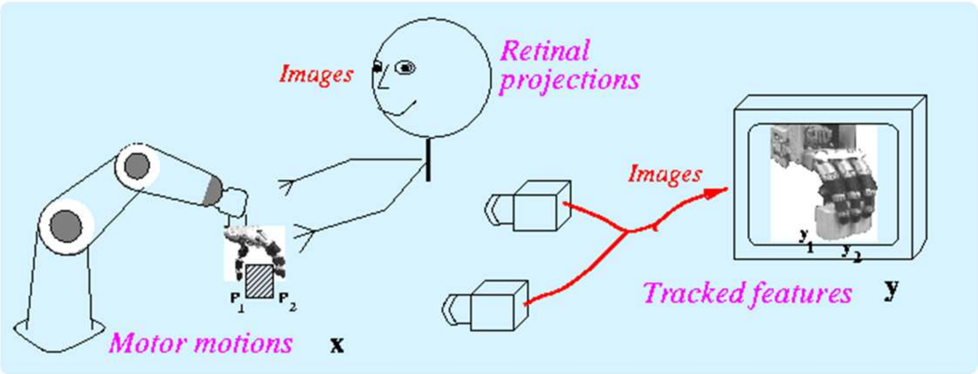


Image-based Visual Servoing

- Observed features: $\mathbf{y} = [\, y_1 \quad y_2 \quad \dots \quad y_m \,]^T$
- Motor joint angles: $\mathbf{x} = [\, x_1 \quad x_2 \dots \quad x_n \,]^T$
- Local linear model: $\Delta\mathbf{y} = \mathbf{J}\Delta\mathbf{x}$
- Visual servoing steps:
  1 Solve: $\mathbf{y}^* - \mathbf{y}_k = \mathbf{J}\Delta\mathbf{x}$
  2 Update: $\mathbf{x}_{k+1} = \mathbf{x}_k + \Delta\mathbf{x}$



Find J Method 1:
Test movements along basis

- Remember: J is unknown m by n matrix

$$\mathbf{J} = \begin{pmatrix} \frac{\partial \mathrm{f}_1}{\partial x_1} & \cdots & \frac{\partial \mathrm{f}_1}{\partial x_n} \\ \vdots & \ddots & \\ \frac{\partial \mathrm{f}_m}{\partial x_1} & & \frac{\partial \mathrm{f}_\mathrm{m}}{\partial x_n} \end{pmatrix}$$

- Motor moves (scale these):

$$\begin{aligned} \Delta\mathbf{x}_1 &= [1, 0, \ldots, 0]^T \\ \Delta\mathbf{x}_2 &= [0, 1, \ldots, 0]^T \\ &\vdots \\ \Delta\mathbf{x}_n &= [0, 0, \ldots, 1]^T \end{aligned}$$

- Suitable $10 < \Delta\mathbf{y} < 20$ pixels
- Finite difference:

$$\mathbf{J} \thickapprox \left(\begin{bmatrix} \vdots \\ \Delta\mathbf{y}_1 \\ \vdots \end{bmatrix} \begin{bmatrix} \vdots \\ \Delta\mathbf{y}_2 \\ \vdots \end{bmatrix} \cdots \begin{bmatrix} \vdots \\ \Delta\mathbf{y}_n \\ \vdots \end{bmatrix} \right)$$

Find J Method 2: Secant Constraints

- Constraint along a line:
- Defines m equations

$$\Delta \mathbf{y} = \mathbf{J} \Delta \mathbf{x}$$

- Collect n arbitrary, but different measures y
- Solve for J

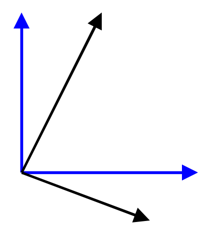
$$\begin{pmatrix} \begin{bmatrix} \cdots & \Delta \mathbf{y}_1^T & \cdots \end{bmatrix} \\ \begin{bmatrix} \cdots & \Delta \mathbf{y}_2^T & \cdots \end{bmatrix} \\ \vdots \\ \begin{bmatrix} \cdots & \Delta \mathbf{y}_n^T & \cdots \end{bmatrix} \end{pmatrix} = \begin{pmatrix} \begin{bmatrix} \cdots & \Delta \mathbf{x}_1^T & \cdots \end{bmatrix} \\ \begin{bmatrix} \cdots & \Delta \mathbf{x}_2^T & \cdots \end{bmatrix} \\ \vdots \\ \begin{bmatrix} \cdots & \Delta \mathbf{x}_n^T & \cdots \end{bmatrix} \end{pmatrix} \mathbf{J}^T$$

Find J Method 3: Recursive Secant Constraints

- Based on initial J and one measure pair $\Delta \mathbf{y}, \Delta \mathbf{x}$
- Adjust J s.t. $\Delta \mathbf{y} = \mathbf{J}_{k+1} \Delta \mathbf{x}$
- Rank 1 update:

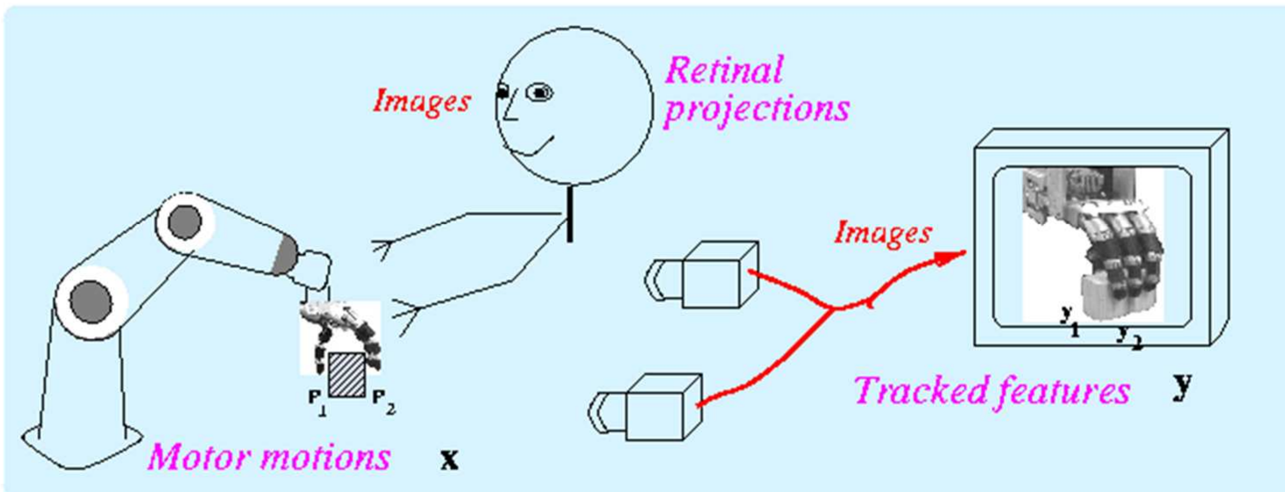
$$\hat{J}_{k+1} = \hat{J}_k + \frac{(\Delta \mathbf{y} - \hat{J}_k \Delta \mathbf{x}) \Delta \mathbf{x}^T}{\Delta \mathbf{x}^T \Delta \mathbf{x}}$$

- Consider rotated coordinates:



  - Update same as finite difference for n orthogonal moves

Achieving visual goals: Uncalibrated Visual Servoing



r e p e a t

1. Solve for motion: $[\mathbf{y}^* - \mathbf{y}_k] = \mathbf{J}\Delta\mathbf{x}$
2. Move robot joints: $\mathbf{x}_{k+1} = \mathbf{x}_k + \Delta\mathbf{x}$
3. Read actual visual move Δy

$$\frac{(\Delta \mathbf{y} - \hat{J}_k \Delta \mathbf{x})\Delta \mathbf{x}^T}{\Delta x^T \Delta x}$$

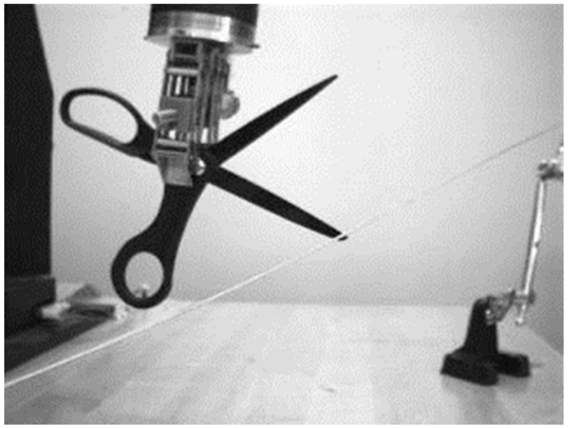
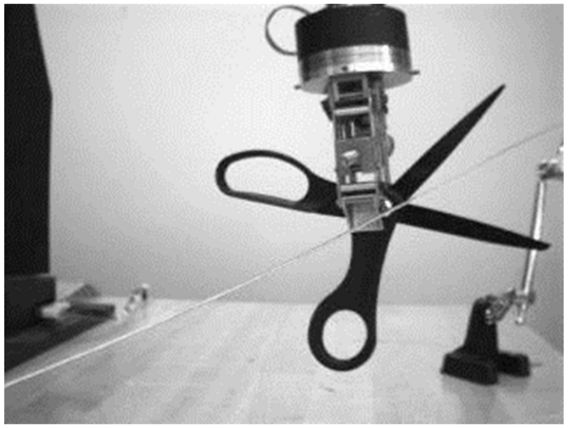
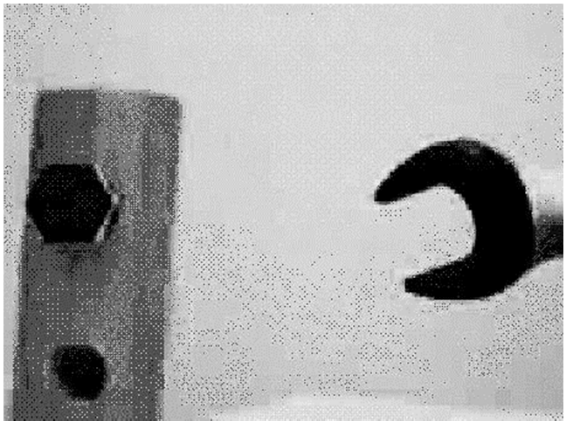
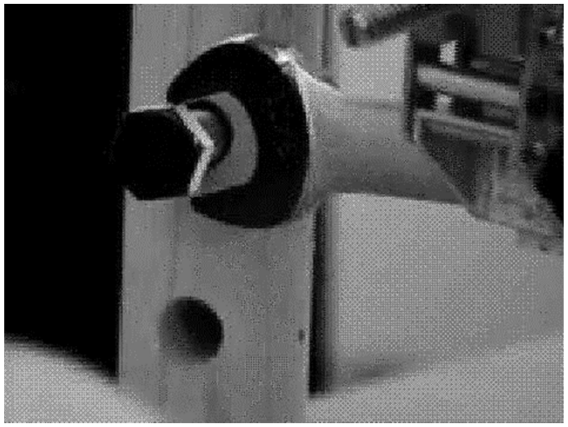
Can we always guarantee when a task is achieved/achievable?

Visually guided motion control

Issues:

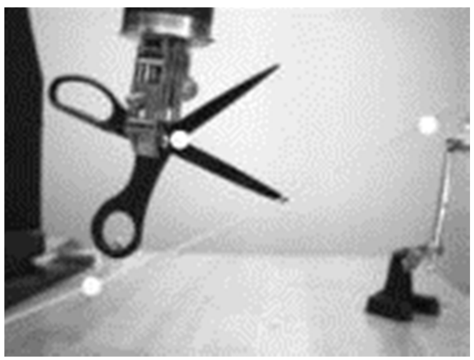
1. What tasks can be performed?
   – Camera models, geometry, visual encodings
2. How to do vision guided movement?
   – H-E transform estimation, feedback, feedforward motion control
3. How to plan, decompose and perform whole tasks?

How to specify a visual task?

Task and Image Specifications

Task function T(x) = 0   Image encoding E(y) =0



task space error

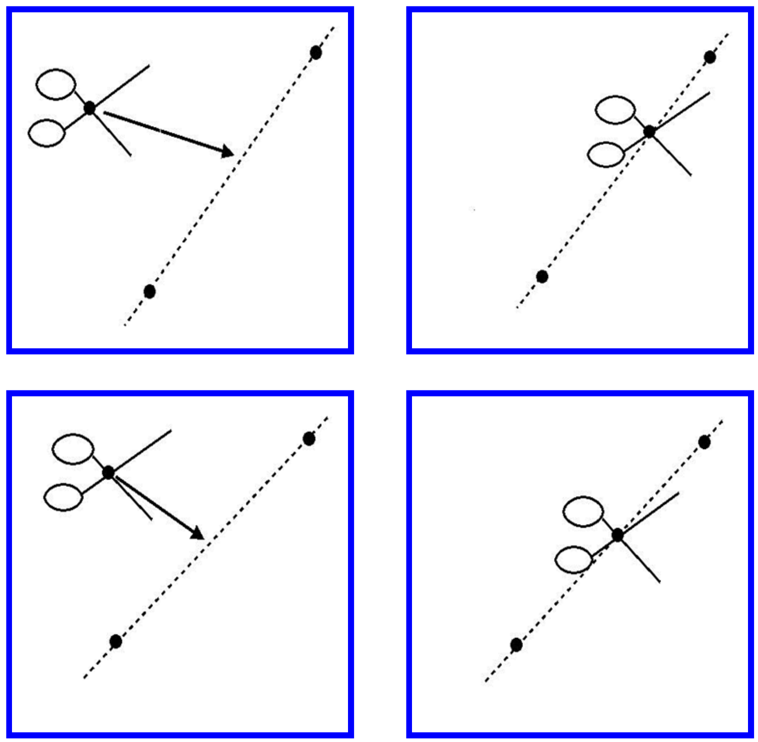
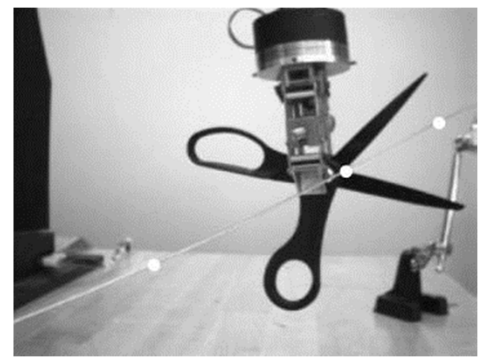


image space error

image space satisfied

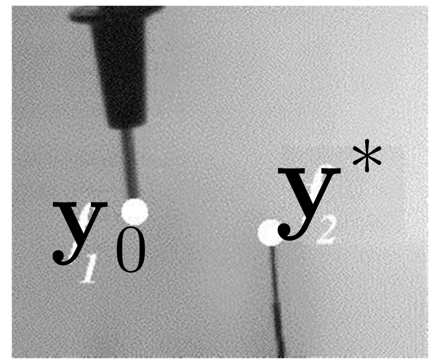


task space satisfied

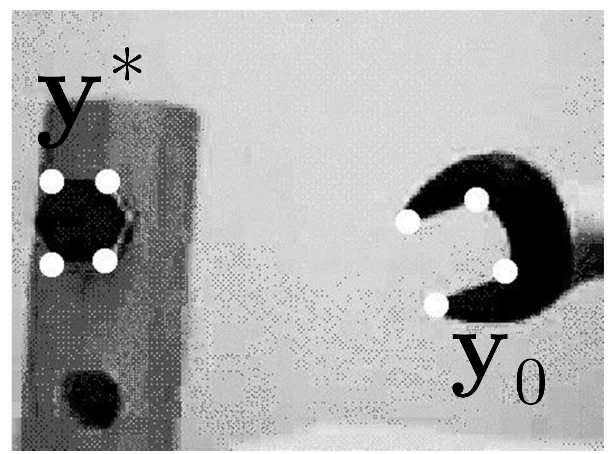
Visual specifications

- Point to Point task “error”:

$$\mathbf{E} = [\mathbf{y}_2^* - \mathbf{y}_0]$$



$$\mathbf{E} = \begin{bmatrix} y_1 \\ \vdots \\ y_{16} \end{bmatrix}^* - \begin{bmatrix} y_1 \\ \vdots \\ y_{16} \end{bmatrix}_0$$



Why 16 elements?

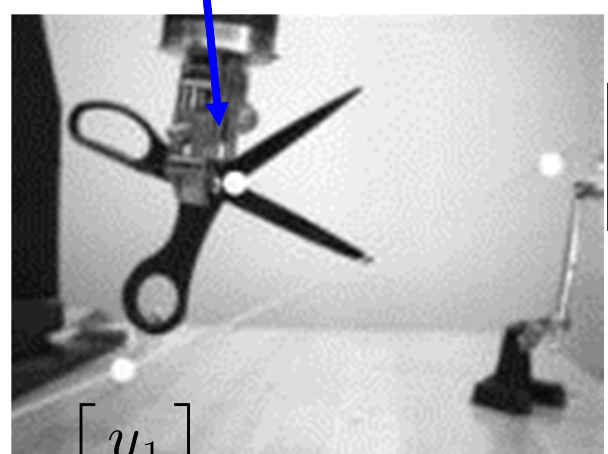
Visual specifications 2

- Point to Line

Line: $$\mathbf{E}_{pl}(\mathbf{y},\mathbf{l}) = \begin{bmatrix} \mathbf{y}_l \cdot \mathbf{l}_l \\ \mathbf{y}_r \cdot \mathbf{l}_r \end{bmatrix}$$

$$\mathbf{l}_l = \begin{bmatrix} y_3 \times y_1 \\ y_4 \times y_2 \end{bmatrix}$$

$$\mathbf{y}_l = \begin{bmatrix} y_5 \\ y_6 \end{bmatrix}$$

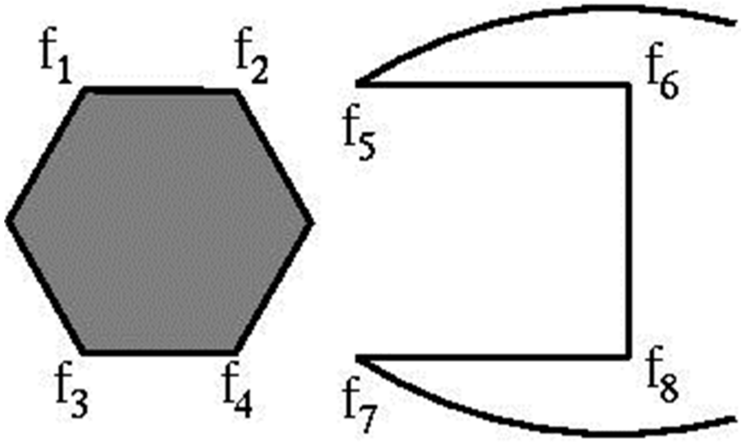


$$\begin{bmatrix} y_3 \\ y_4 \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$$

Note: y homogeneous coord.

Parallel Composition example



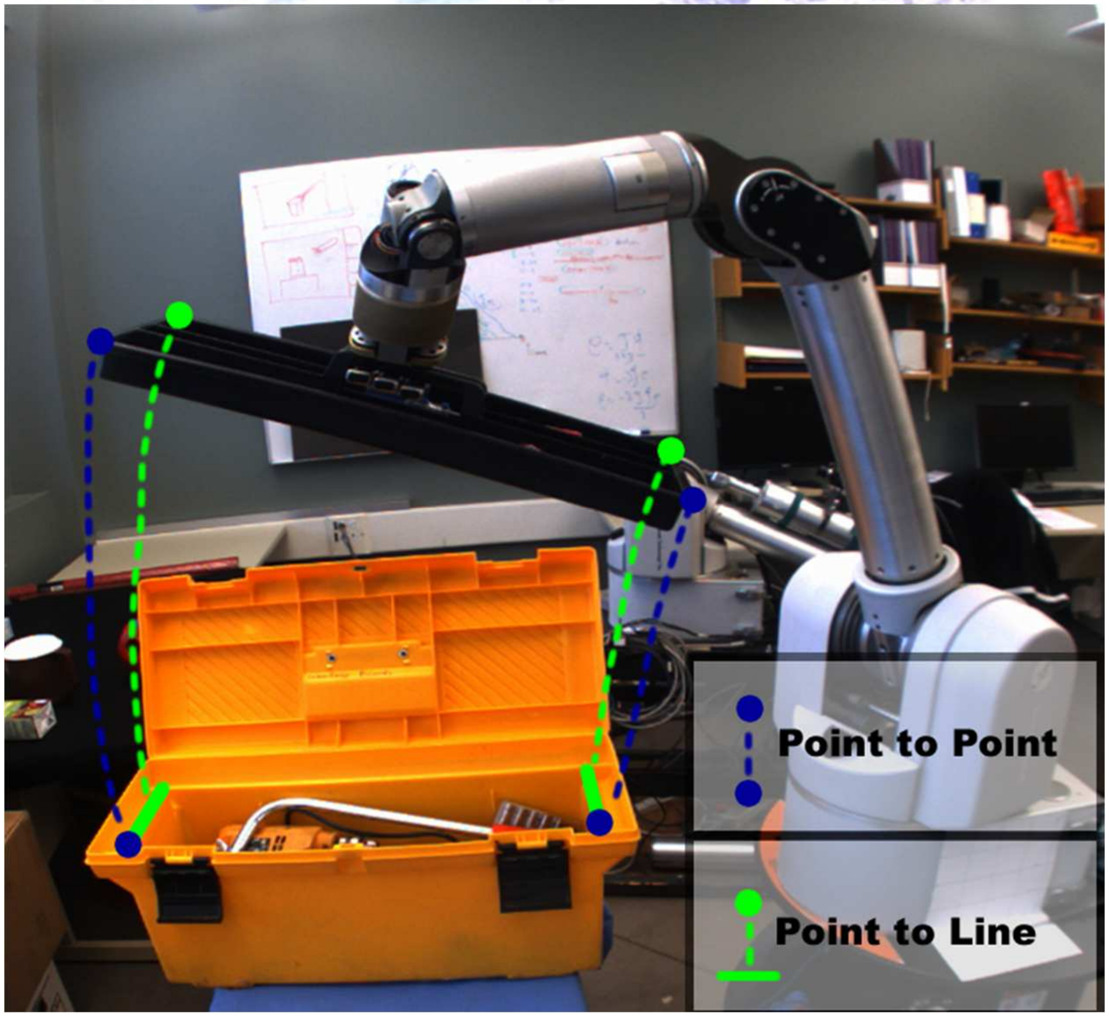
$$E_{\text{wrench}}(y) = \begin{bmatrix} y_2 - y_5 \\ y_4 - y_7 \\ y_6 \bullet (y_1 \times y_2) \\ y_8 \bullet (y_3 \times y_4) \end{bmatrix}$$

(plus e.p. checks)

5.4. Visual specifications

- Image commands = Geometric constraints in image space

- HRI: User points/clicks on features in an image
- Robot controller drives visual error to zero



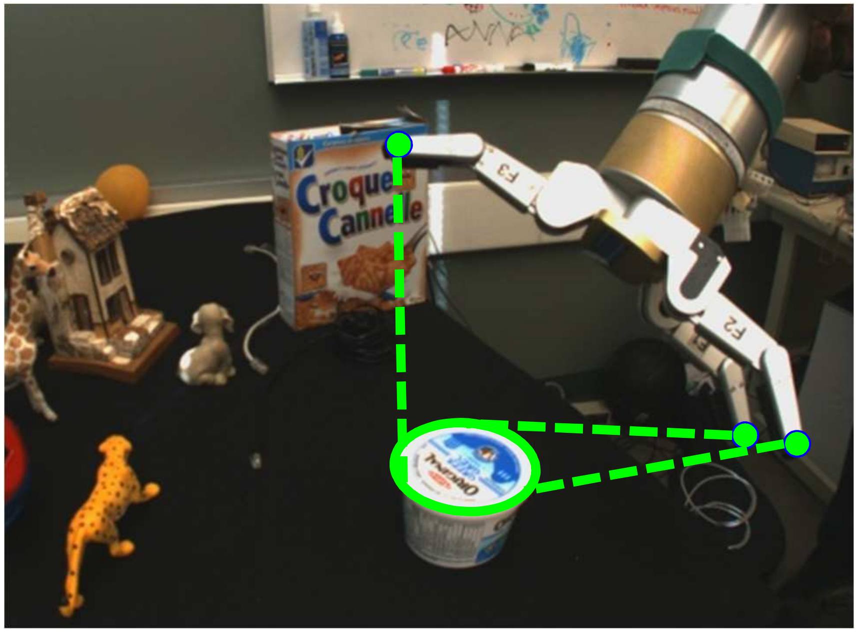
Visual Specifications

Additional examples:

- Point to conic

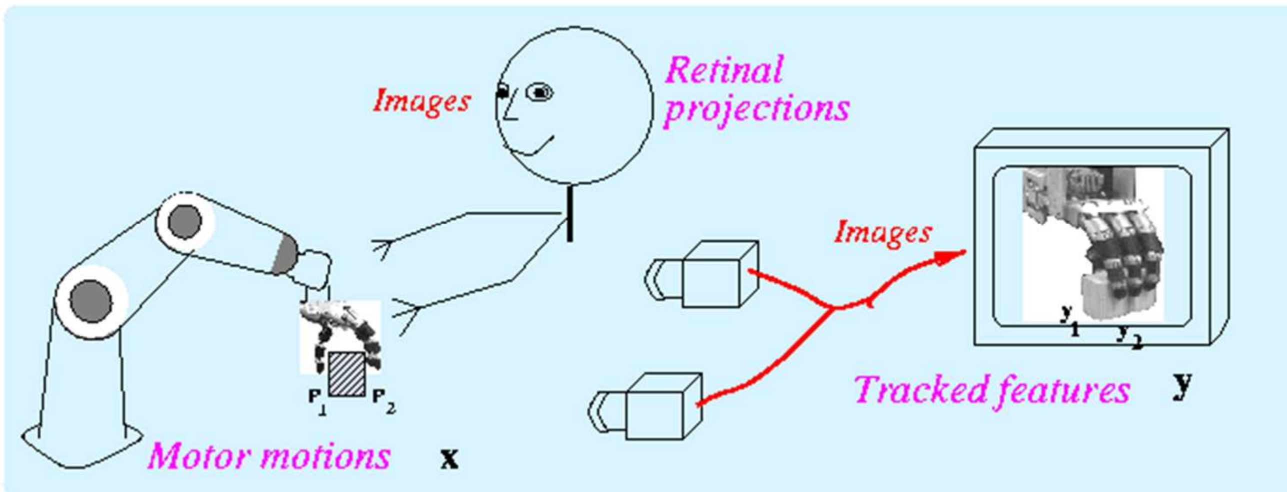
  Identify conic C from 5 pts on rim

  Error function yCy’



- Point(s) to plane
- Plane to plane
- Etc.

Achieving visual goals: Uncalibrated Visual Servoing



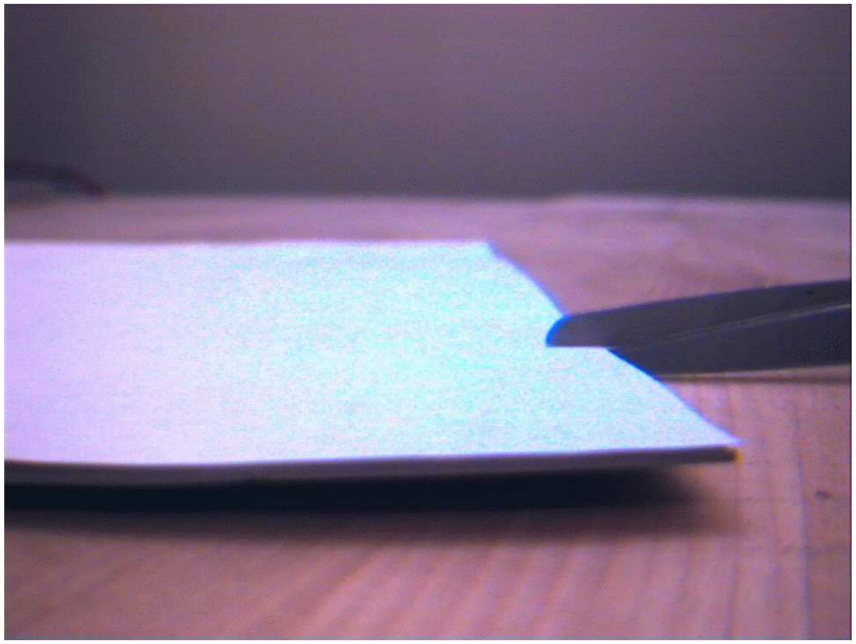
repeat

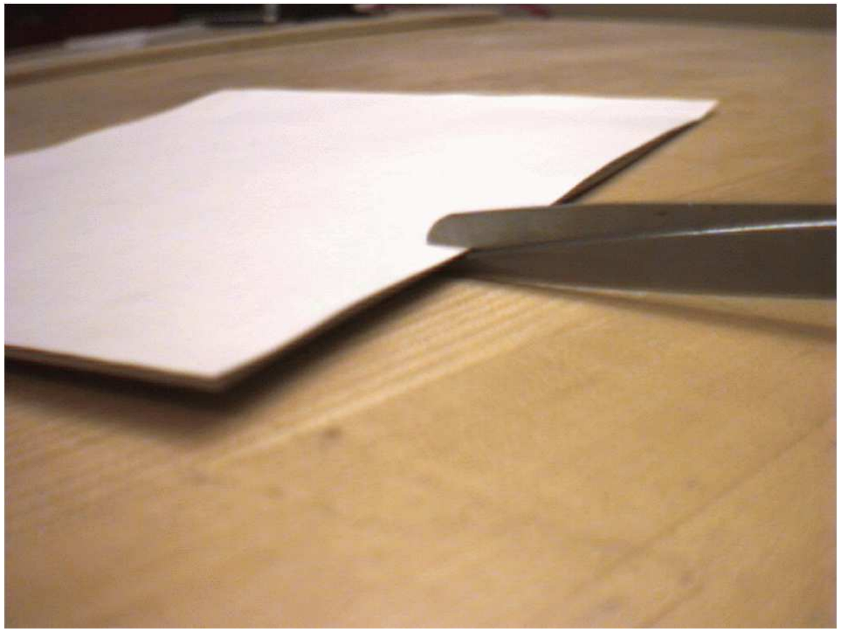
1. Solve for motion: $[\mathbf{y}^* - \mathbf{y}_k] = \mathbf{J}\Delta\mathbf{x}$
2. Move robot joints: $\mathbf{x}_{k+1} = \mathbf{x}_k + \Delta\mathbf{x}$
3. Read actual visual move Δy

$$\frac{(\Delta\mathbf{y} - \hat{J}_k\Delta\mathbf{x})\Delta\mathbf{x}^T}{\Delta x^T \Delta x}$$

Can we always guarantee when a task is achieved/achievable?

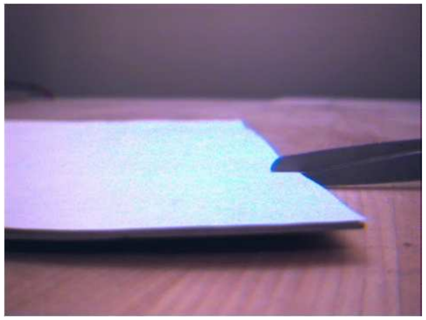
Task ambiguity

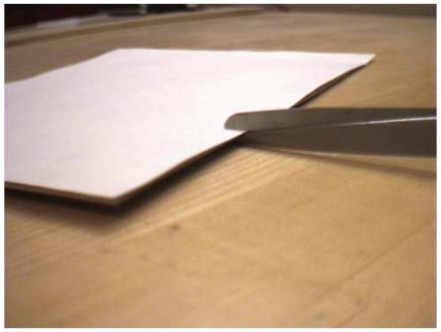


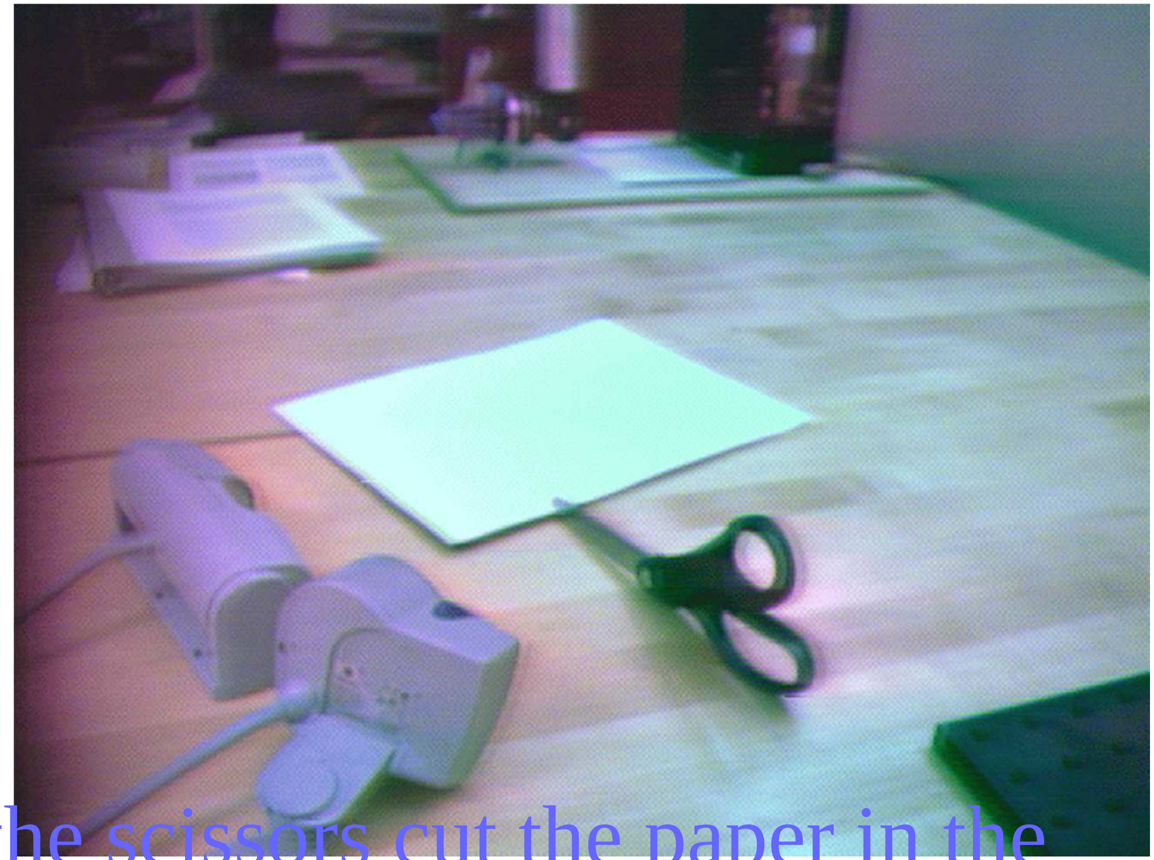


- Will the scissors cut the paper in the middle?

Task ambiguity

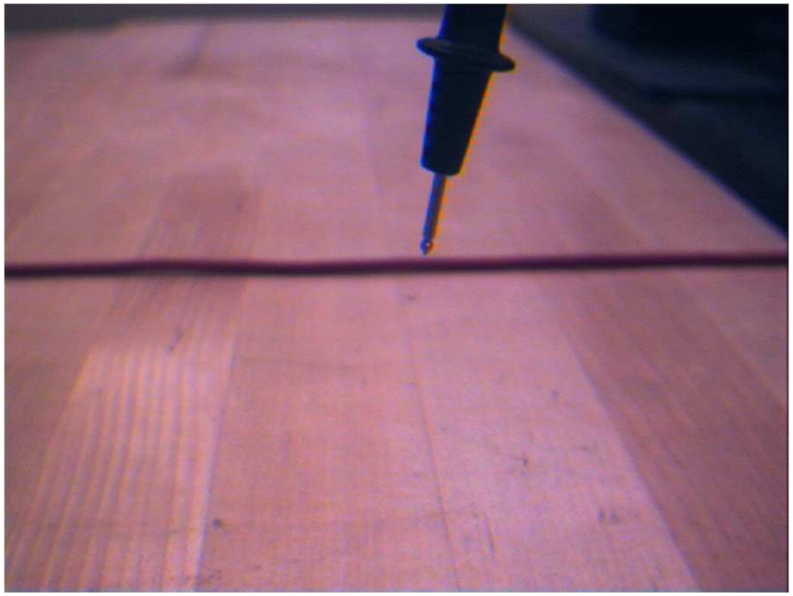


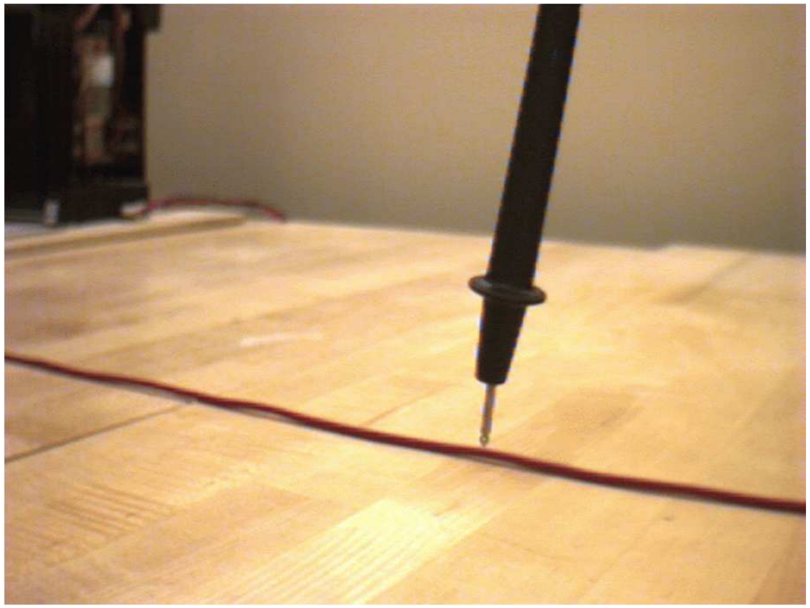




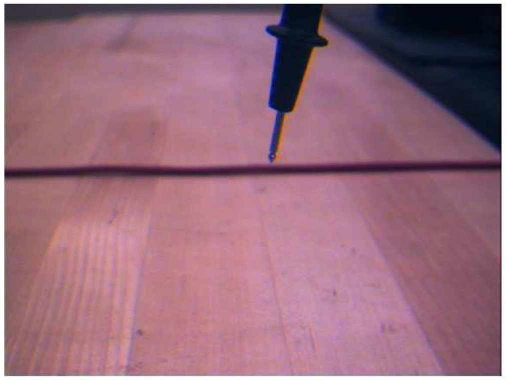
- Will the scissors cut the paper in the middle? **NO!**

Task Ambiguity

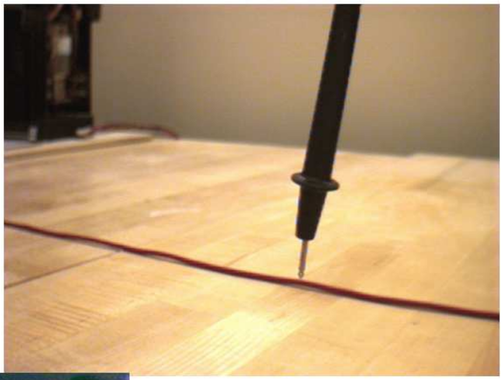


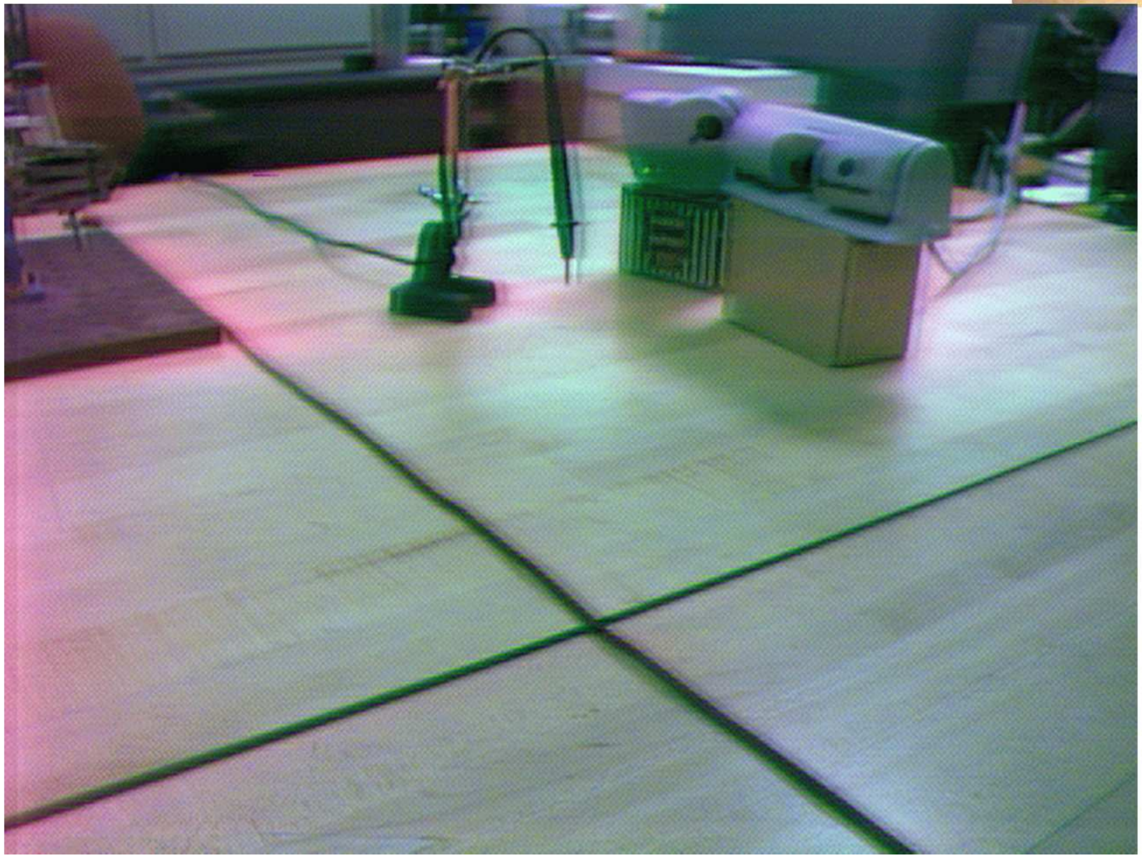


- Is the probe contacting the wire?



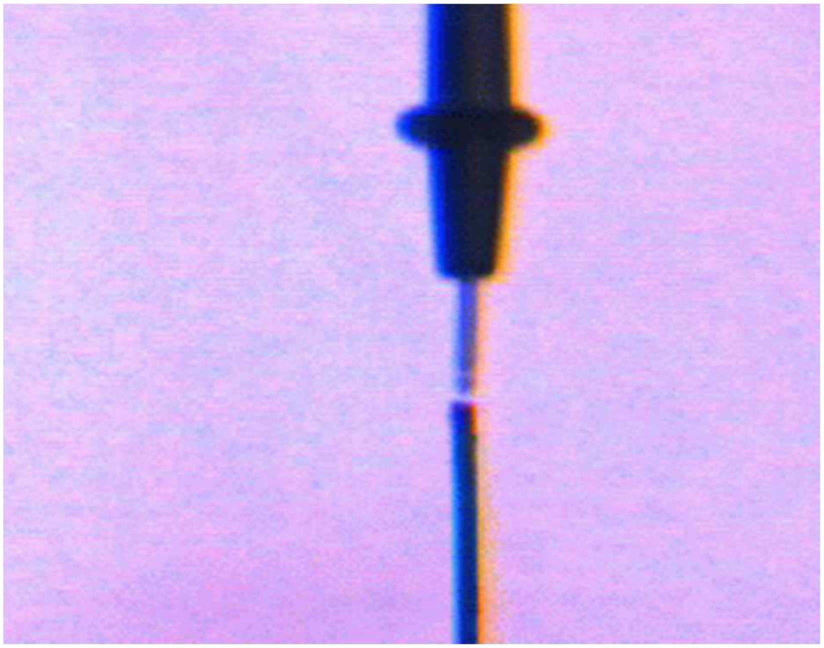
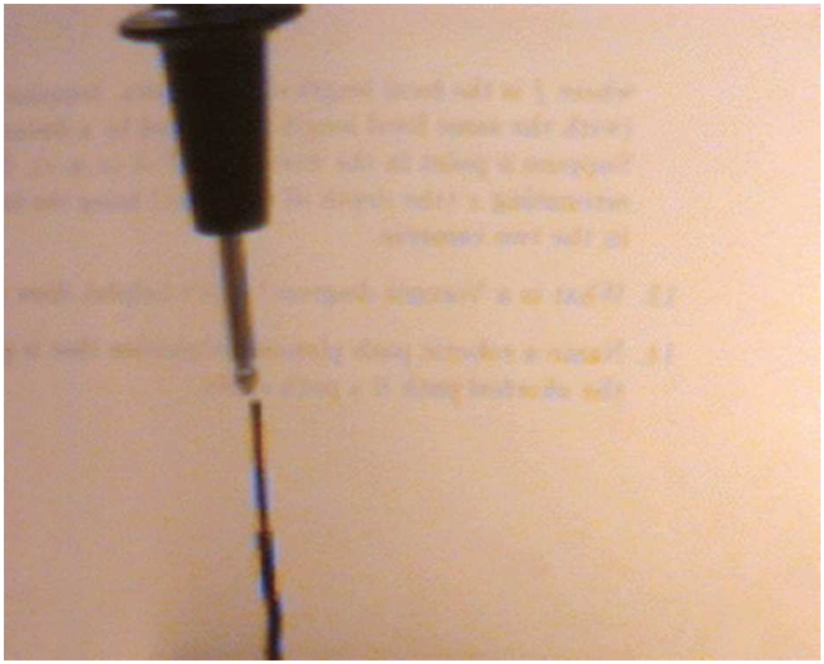
Task Ambiguity



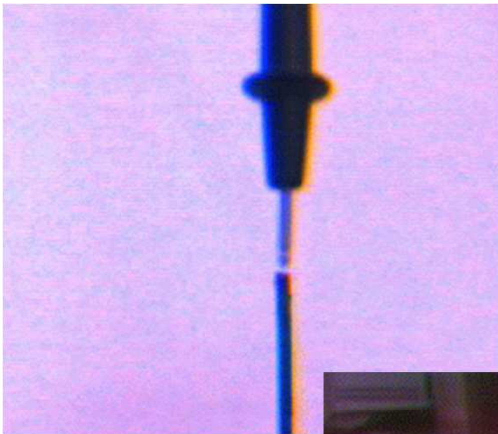


- Is the probe contacting the wire? **NO!**

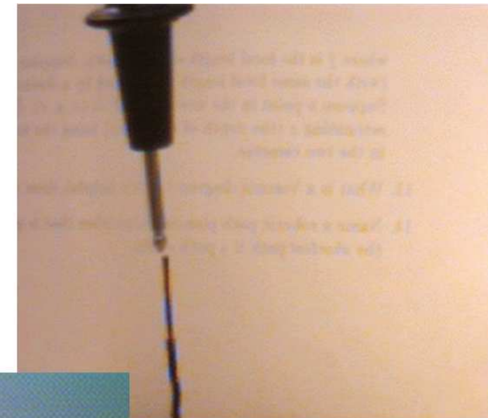
Task Ambiguity

- Is the probe contacting the wire?



Task Ambiguity



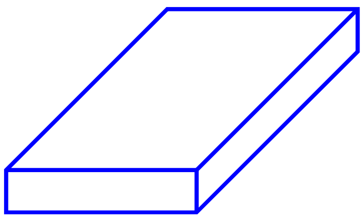
- Is the probe contacting the wire? **NO!**

Task decidability and invariance

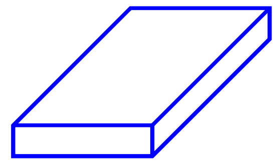
A task $T(f)=0$ is invariant under a group G_x of transformations, iff

$$\forall f \in V^n,\ g \in G_x \text{ with } g(f) \in V^n \qquad T(f)=0 \Leftrightarrow T(g(f))=0$$

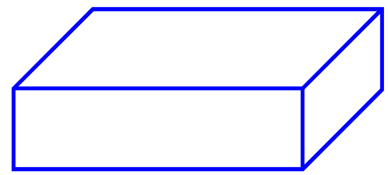
If $T(f) = 0$ here,



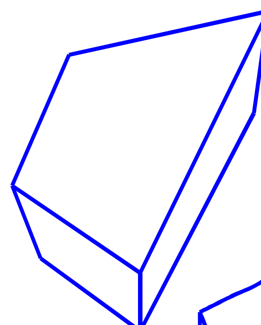
$T(f)$ must be 0 here, if T is G_{sim} invariant



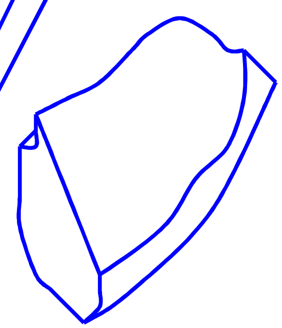
$T(f)$ must be 0 here, if T is G_{aff} invariant



$T(f)$ must be 0 here, if T is G_{proj} invariant



$T(f)$ must be 0 here, if T is G_{inj} invariant



All achievable tasks…

One point $\begin{bmatrix}1\\0\\0\\0\end{bmatrix}$

Coincidence $\begin{bmatrix}1&1\\0&0\\0&0\\0&0\end{bmatrix}$

Noncoincidence $\begin{bmatrix}1&0\\0&1\\0&0\\0&0\end{bmatrix}$

3pt. coincidence $\begin{bmatrix}1&1&1\\0&0&0\\0&0&0\\0&0&0\end{bmatrix}$

2pt. coincidence $\begin{bmatrix}1&1&0\\0&0&1\\0&0&0\\0&0&0\end{bmatrix}$

Collinearity $\begin{bmatrix}1&0&1\\0&1&1\\0&0&0\\0&0&0\end{bmatrix}$

General Position $\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\\0&0&0\end{bmatrix}$

4pt. coincidence $\begin{bmatrix}1&1&1&1\\0&0&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}$

2 2pt. coincidence $\begin{bmatrix}1&1&0&0\\0&0&1&1\\0&0&0&0\\0&0&0&0\end{bmatrix}$

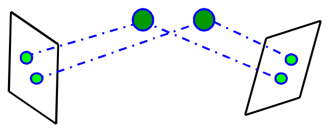
Cross Ratio $\begin{bmatrix}1&0&1&\alpha\\0&1&1&1\\0&0&0&0\\0&0&0&0\end{bmatrix}$

Coplanarity $\begin{bmatrix}1&0&0&1\\0&1&0&1\\0&0&1&1\\0&0&0&0\end{bmatrix}$

General Position $\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$

are ALL projectively distinguishable coordinate systems

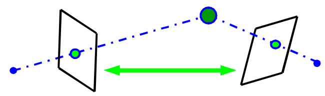
Composing possible tasks



Injective C_{inj}

T_{pp} point-coincidence

Task primitives



Projective C_{wk}

T_{pp}

T_{col} collinearity

T_{copl} coplanarity

$T_{cr\alpha}$ cross ratios (α)

AND

$$T_1 \wedge T_2 = \begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$$

OR

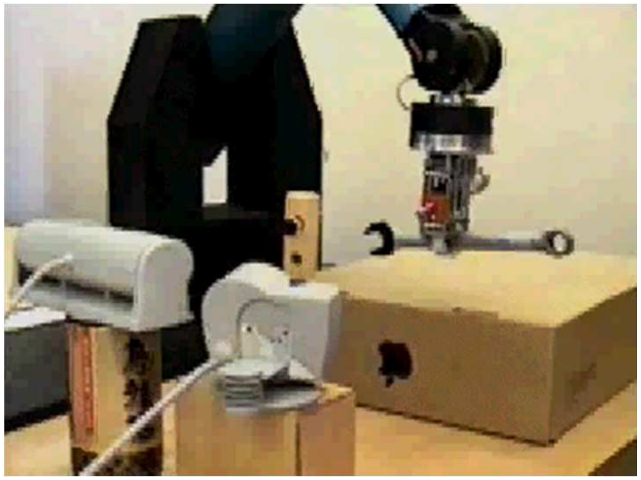
$$T_1 \vee T_2 = T_1 \cdot T_2$$

NOT

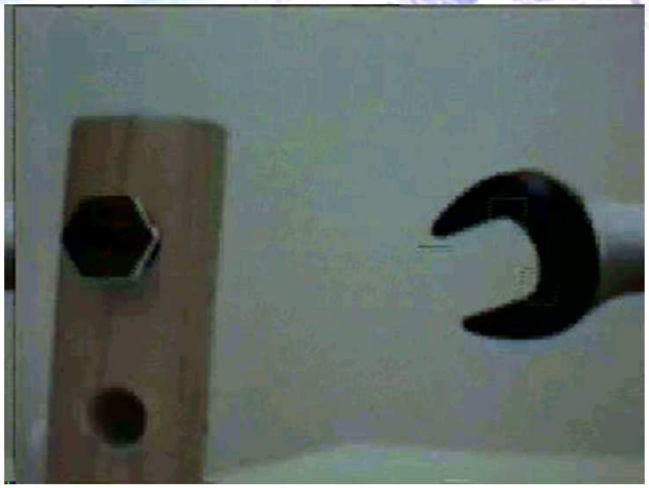
$$\neg T = \begin{cases} 0 & \text{if } T \neq 0 \\ 1 & \text{otherwise} \end{cases}$$

Task operators

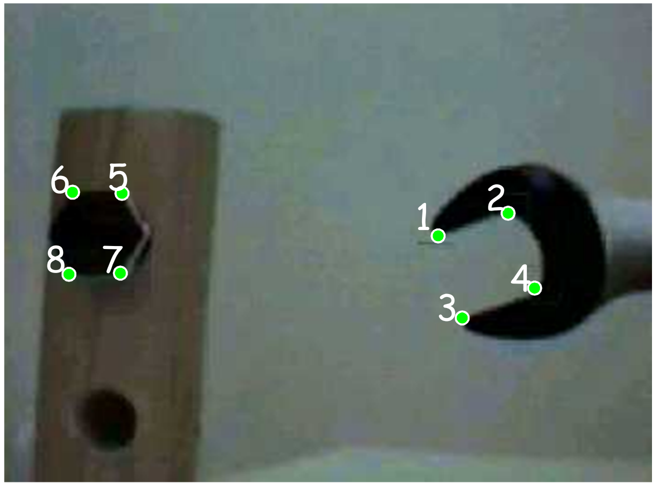
Result: Task toolkit



wrench: view 1



wrench: view 2



$$T_{wrench}(x_{1..8}) = \begin{array}{l} T_{pp}(x_1,x_5) \wedge \\ T_{pp}(x_3,x_7) \wedge \\ T_{col}(x_4,x_7,x_8) \wedge \\ T_{col}(x_2,x_5,x_6) \end{array}$$

Serial Composition
Solving whole real tasks

- Task primitive/"link"

$$A = (\mathbf{E}^{\mathrm{init}}, M, \mathbf{E}^{\mathrm{final}})$$

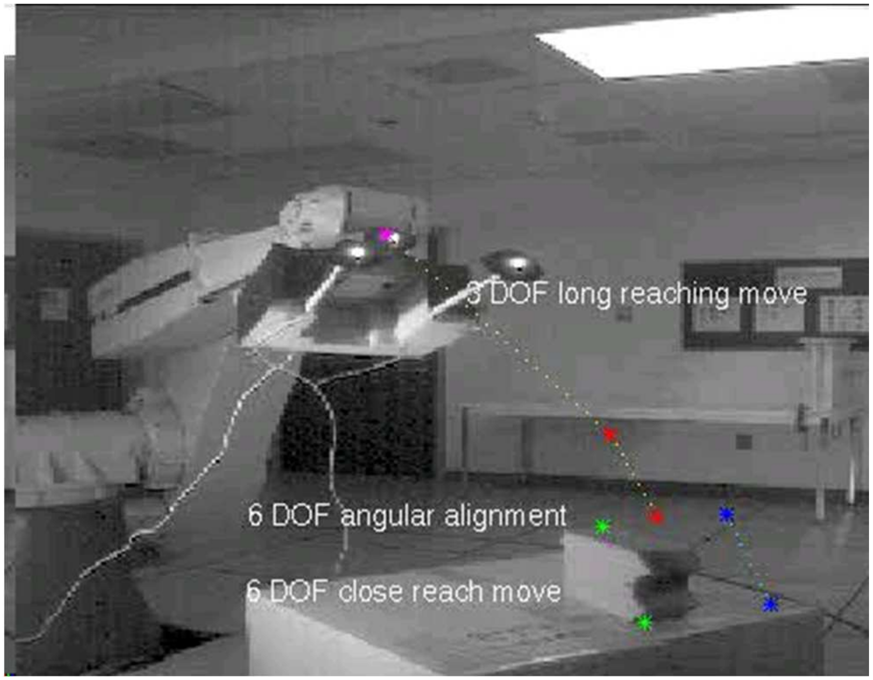
1. Acceptable initial (visual) conditions
2. Visual or Motor constraints to be maintained
3. Final desired condition

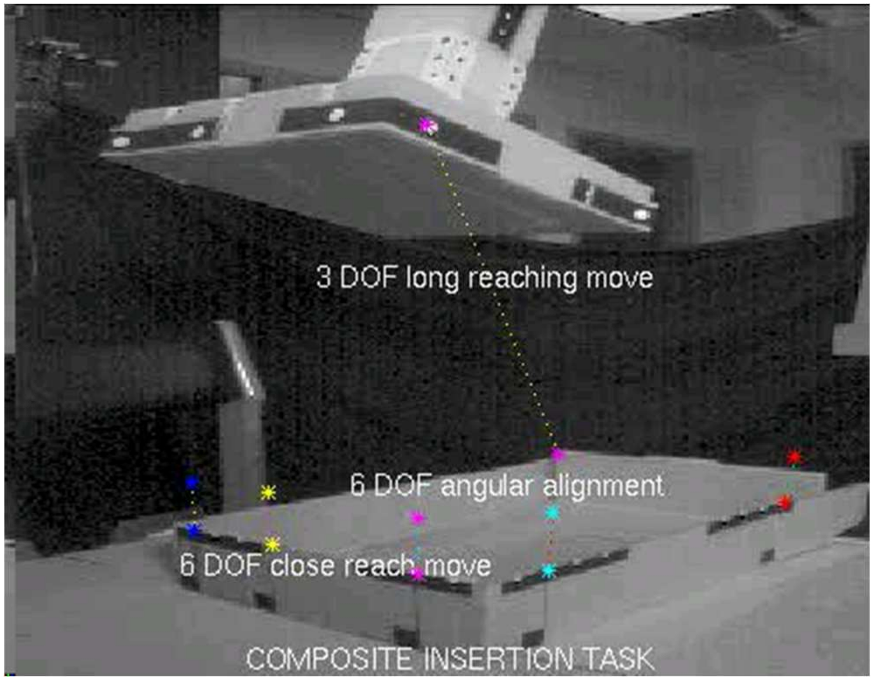
- Task = $A_1 A_2 \ldots A_k$

“Natural” primitive links

1. Transportation
   - Coarse primitive for large movements
   - <= 3DOF control of object centroid
   - Robust to disturbances
2. Fine Manipulation
   - For high precision control of both position and orientation
   - 6DOF control based on several object features

Example:
Pick and place type of movement





3. Alignment???

- To match transport final to fine manipulation initial conditions

More primitives

4. Guarded move
   – Move along some direction until an external contraint (e.g. contact) is satisfied.

5. Open loop movements:
   - When object is obscured
   - Or ballistic fast movements
   - Note can be done based on previously estimated Jacobians

Solving the puzzle…

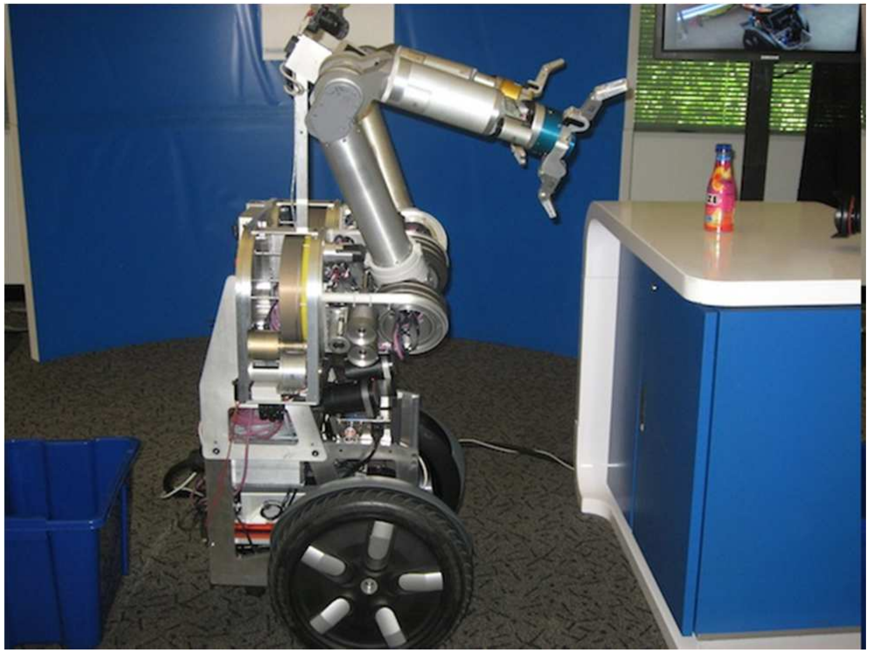
Conclusions

- Visual servoing: The process of minimizing a visually-specified task by using visual feedback for motion control of a robot.

- Is it *difficult*? Yes.
  - Controlling 6D pose of the end-effector from 2D image features.
  - Nonlinear projection, degenerate features, etc.
- Is it important? Of course.
  - Vision is a versatile sensor.
  - Many applications: industrial, health, service, space, humanoids, etc.

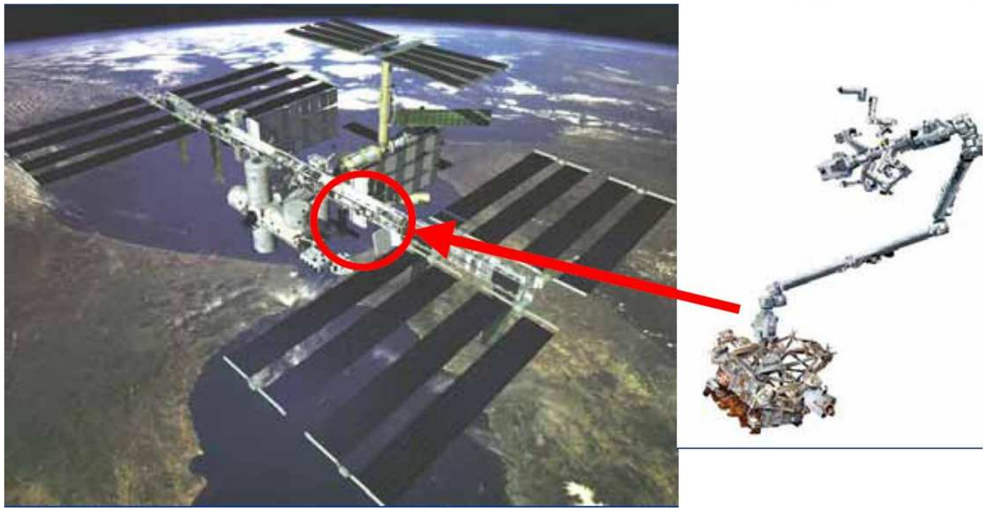
What environments and tasks are of interest?

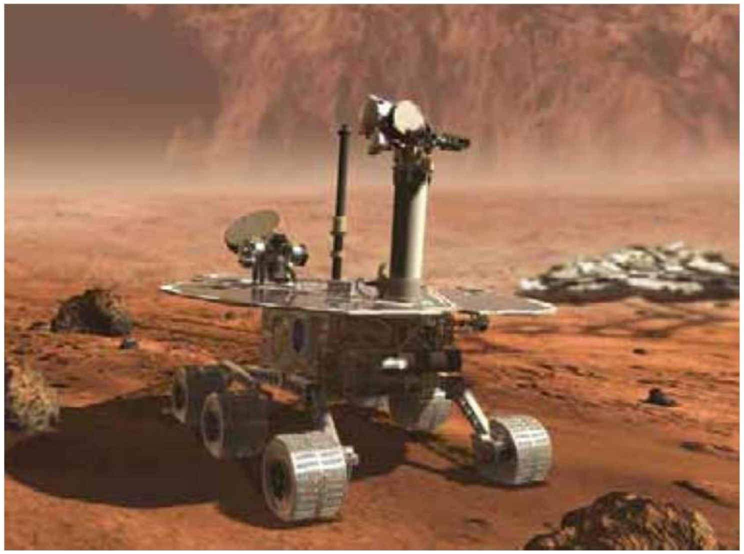
- Not the previous examples.
  - Could be solved "structured"
- Want to work in everyday unstructured environments



Use in space applications

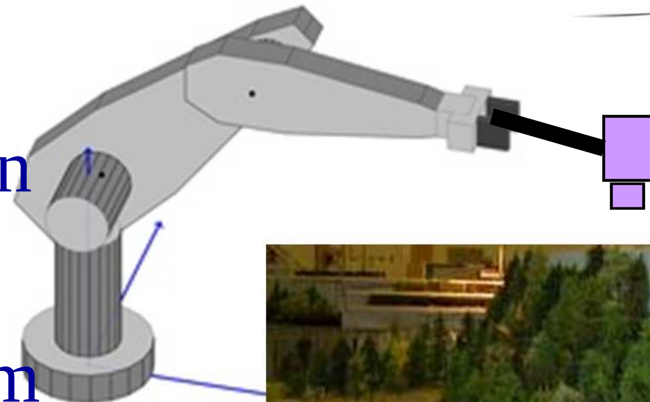
- Space station
- On-orbit service
- Planetary Exploration

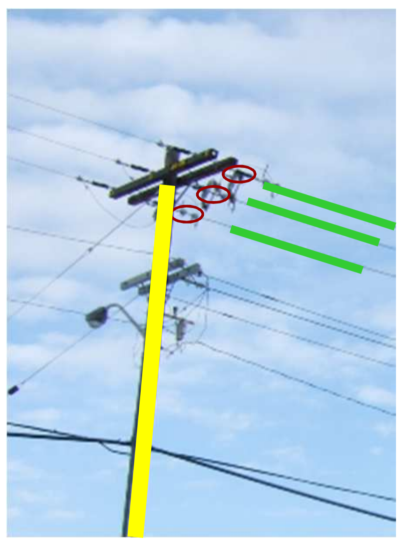




Power line inspection

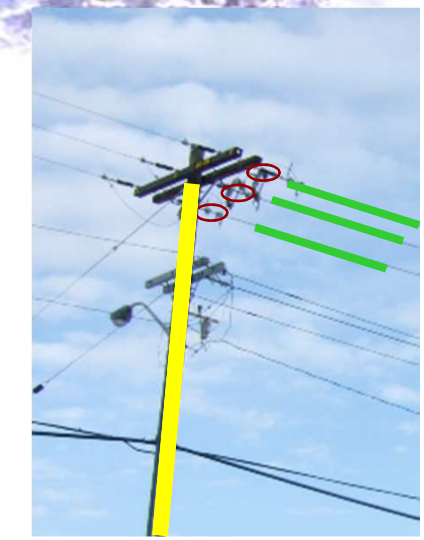
- A electric UAV carrying camera flown over the model
- Simulation: Robot arm holds camera





Model landscape: Edmonton railroad society

Use in Power Line Inspection



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