IVR: Visual Servoing

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Overview

- Model-based control
- Visual servoing task
- What is a Jacobian?
- Visual servoing task
- Implications for robot control
PROBLEM: Guiding a robot to a target based on images

APPLICATIONS:

- Assembly robotics: Component insertion
- Mobile robotics: Docking

⇒ VISUAL SERVOING THEORY
If only vertical robot motion possible (and sufficient) to reduce the gap:

How to get peg exactly into hole?
APPROACH 1: MODEL DRIVEN

KNOWN:
- Robot manipulation model
- Part & robot position known
- Target model
- Camera calibrated

BUT: errors exist and combine - noise, unknowns, gear backlash

SO: need very accurate calibration & mechanisms
TRY 2: VISUAL SERVOING

Move so that observed positions directly link to task distances

- Incrementally move to reduce image gap
- Don’t know exact positions

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MORE FORMAL MODEL

CONSIDER:

CAMERA

TARGET

C

SCENE

B

TOOL TIP

R(\theta)

\theta : JOINT PARAMETERS

ROBOT
VARIOUS QUANTITIES

$B$ - ROBOT POSITION WRT SCENE

$C$ - CAMERA POSITION WRT SCENE

$P$ - CAMERA PROJECTION MODEL

$\vec{\theta}$ - ROBOT JOINT PARAMETERS

$R(\vec{\theta})$ - TOOL POSITION WRT ROBOT
LINKING EQUATION

IF:

- \( \vec{x} \) - TOOL TIP WRT TOOL
- \( \vec{z} \) - TARGET WRT SCENE
- \( \vec{a} \) - IMAGE OF TOOL TIP
- \( \vec{b} \) - IMAGE OF TARGET

THEN (as a concatenation of appropriate transformations):

- \( \vec{a} = PC^{-1} BR(\theta) \vec{x} \)
- \( \vec{b} = PC^{-1} \vec{z} \)

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APPROACH 1: MODEL DRIVEN

Calibrate $P, C, B, R(\theta)$ accurately

SOLVE: $\theta = f(\bar{z}, \bar{x}, P, C, B)$

Hard analytics

Not always solvable
How much to move joints ($\Delta \vec{\theta}$) to reduce target error $\vec{\Delta} = \vec{a} - \vec{b}$?

Visually estimate $\vec{f}(\cdots)$ such that $\Delta \vec{\theta} \doteq \vec{f}(\vec{\Delta})$

Use $\Delta \vec{\theta}$ to partially approach target and recompute $\vec{\theta}$

Iterate
Move robot joint $i$ slightly from $\theta_i$ to $\theta_i + \varepsilon$

Observe tool tip moves slightly from $\vec{a}$ to $\vec{a} + \vec{\delta}_i$

Compute:

$$\frac{\partial \vec{a}}{\partial \theta_i} = \frac{\left( \vec{a} + \vec{\delta}_i \right) - \vec{a}}{(\theta_i + \varepsilon) - \theta_i} = \frac{\vec{\delta}_i}{\varepsilon}$$

Repeat for all $i$ to estimate JACOBIAN matrix $J$

$$J = \frac{1}{\varepsilon} \left[ \vec{\delta}_1, \ldots, \vec{\delta}_N \right]$$

for $N$ joints.
Linear theory:

\[ \Delta = J \Delta \vec{\theta} \]

\( J \) is \( 2 \times N \), so use pseudo-inverse

\[ \Delta \vec{\theta} = (J^T J)^{-1} J^T \Delta \]

But \( J \) is only approximate and not true inverse?

So, move \( \alpha \Delta \vec{\theta} \) and iterate \( (\alpha < 1) \)
see Perceptual Actions: Vision Based Uncalibrated Robot Control by Martin Jägersand
DO

Compute $\vec{\Delta}$

Estimate $J$

Compute $\Delta \hat{\theta}$

Move joints $\alpha \Delta \hat{\theta}$ where $0 < \alpha < 1$

WHILE $\| \vec{\Delta} \| > \tau$ pixels

$\tau > 1$? Maybe robot is ‘shakey’
If $\alpha$ small enough, should always be reducing $\Delta$

As $J$ is linear, moving $\alpha \Delta \vec{\theta}$ should reduce position error by approximately $\alpha \Delta$
<table>
<thead>
<tr>
<th>STEP</th>
<th>MOVEMENT</th>
<th>REMAINDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\alpha | \vec{\Delta} |$</td>
<td>$(1 - \alpha) | \vec{\Delta} |$</td>
</tr>
<tr>
<td>2</td>
<td>$(1 - \alpha) \alpha | \vec{\Delta} |$</td>
<td>$(1 - \alpha)^2 | \vec{\Delta} |$</td>
</tr>
<tr>
<td></td>
<td>$\ldots$</td>
<td>$\vdots$</td>
</tr>
<tr>
<td>$n$</td>
<td>$(1 - \alpha)^{n-1} \alpha | \vec{\Delta} |$</td>
<td>$(1 - \alpha)^n | \vec{\Delta} |$</td>
</tr>
</tbody>
</table>

Total movement:

$$\sum_{n=1}^{\infty} (1 - \alpha)^{n-1} \alpha \| \vec{\Delta} \| = \frac{1}{1 - (1 - \alpha) \| \vec{\Delta} \|} \alpha \| \vec{\Delta} \| = \| \vec{\Delta} \|$$
Initial position and histogram (#pixels per gray level)

Camera on side
Note: changing binary images

5 iterations
Discussion

- Usually more cameras (image-based visual servoing)
- If the pose of the robot can be estimated based on a robot model a single camera may be sufficient (position-based visual servoing)
- Precision is improved by combination with force feedback
- Camera movements and other sources of errors
- Related problem: Camera positioning; track following in autonomous robots
Summary on visual servoing

- Servoing versus model based control
- Basics of visual servoing
- Linear approximations are usually safe if small steps are taken
- What about efficiency, dynamics, inertia, friction?
  ⇒ control theory

Java-based Visual Servo Simulator:
http://www.robot.uji.es/research/projects/javiss

Further reading: