Introduction to Vision-Based Motion Control of Robots

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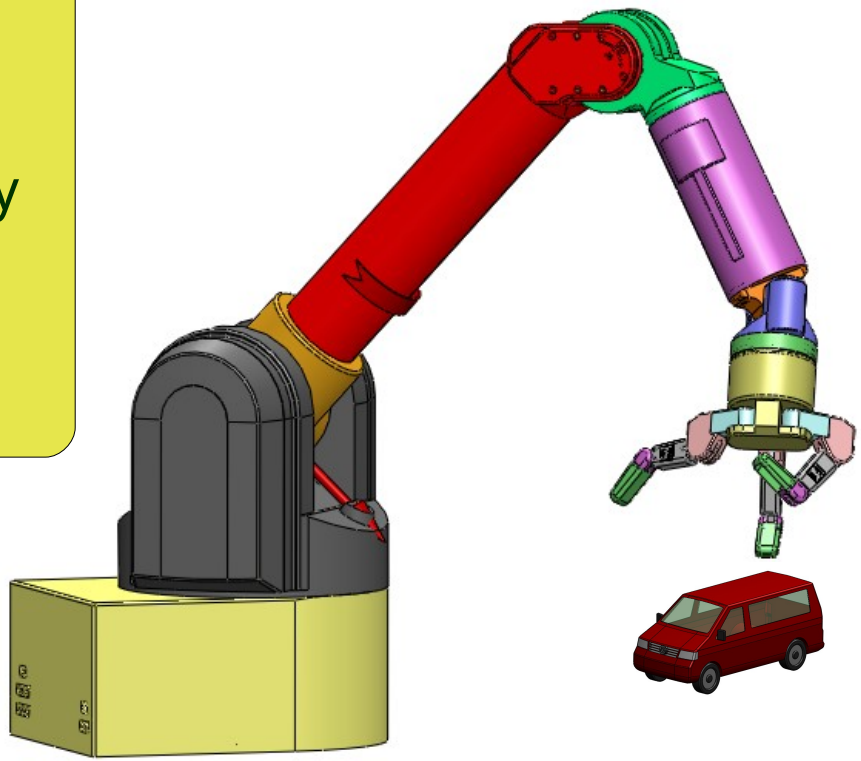
INFORMATICS iCORE CIRCLE OF RESEARCH EXCELLENCE

Vision-Based Control

Do something useful, robot!

Pick up the toy car!

Use cameras.



Vision-Based Control

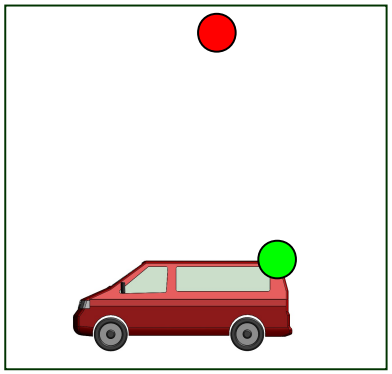
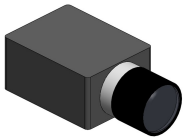
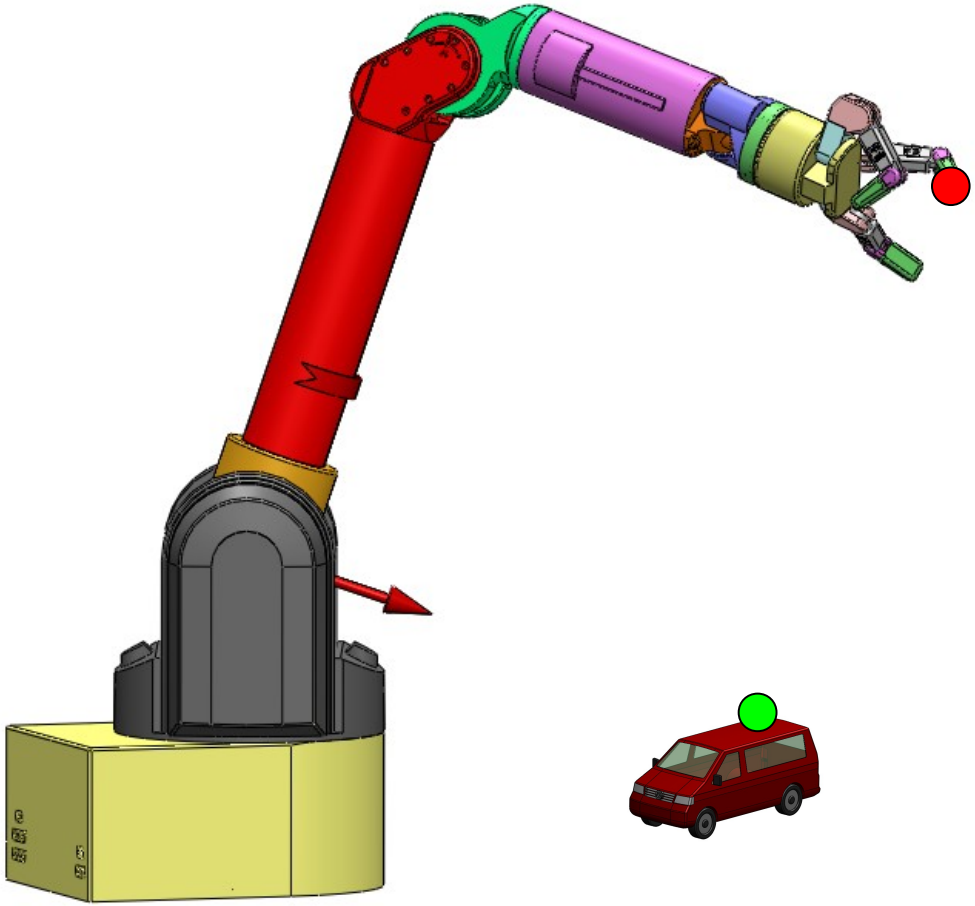
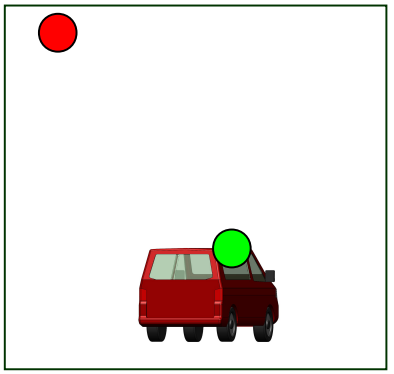


Image 1







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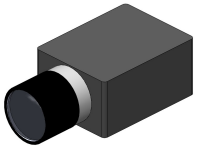

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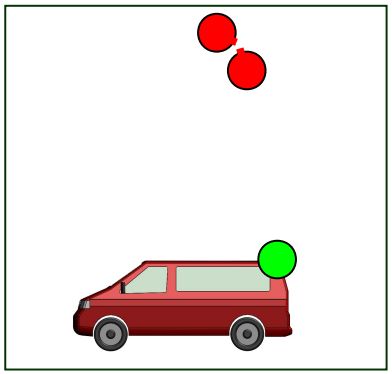

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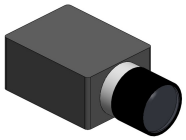

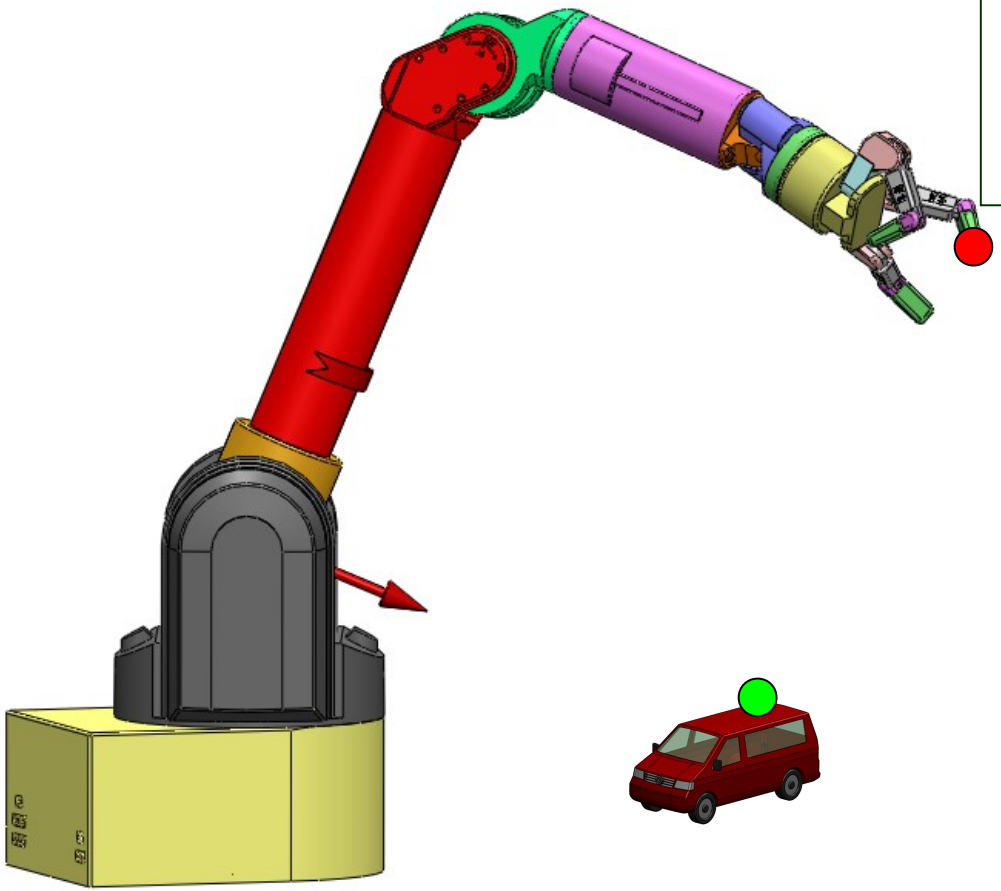

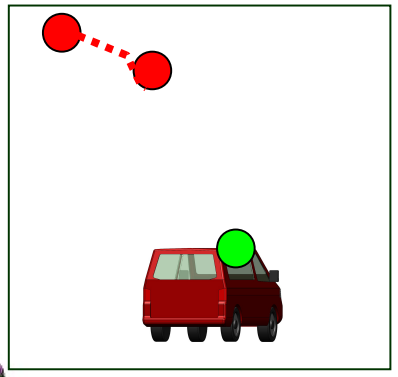

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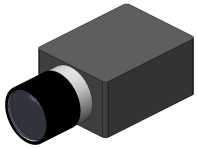

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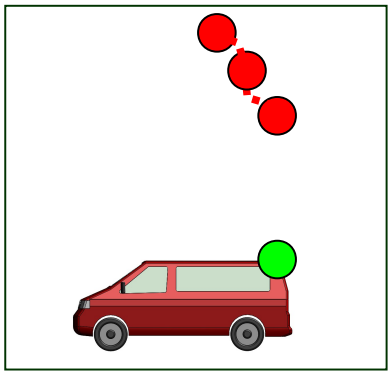

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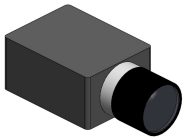

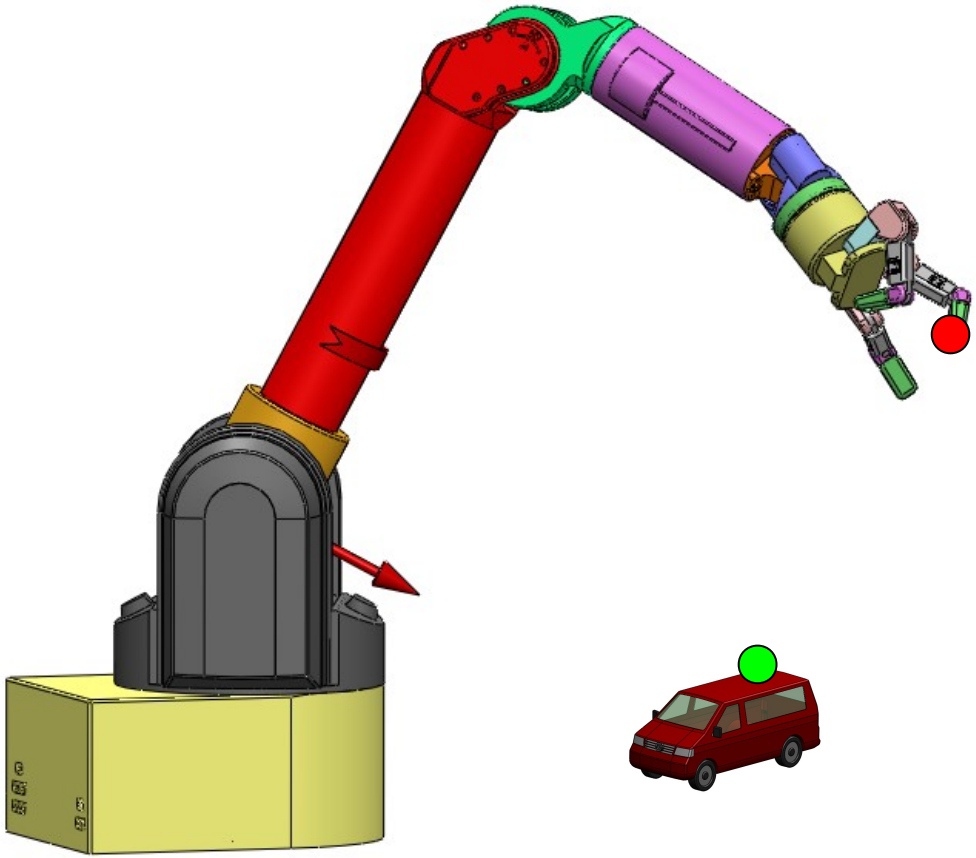

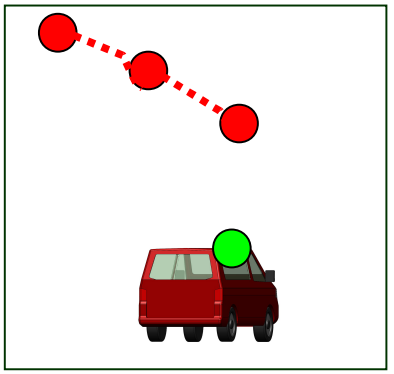

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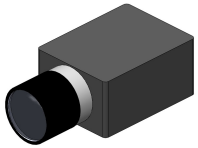

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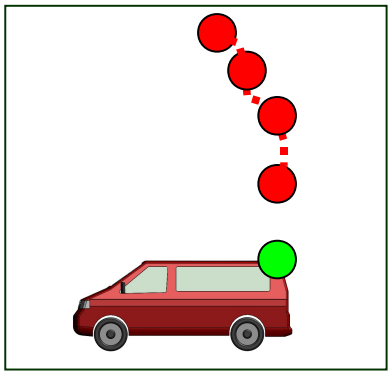

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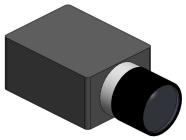

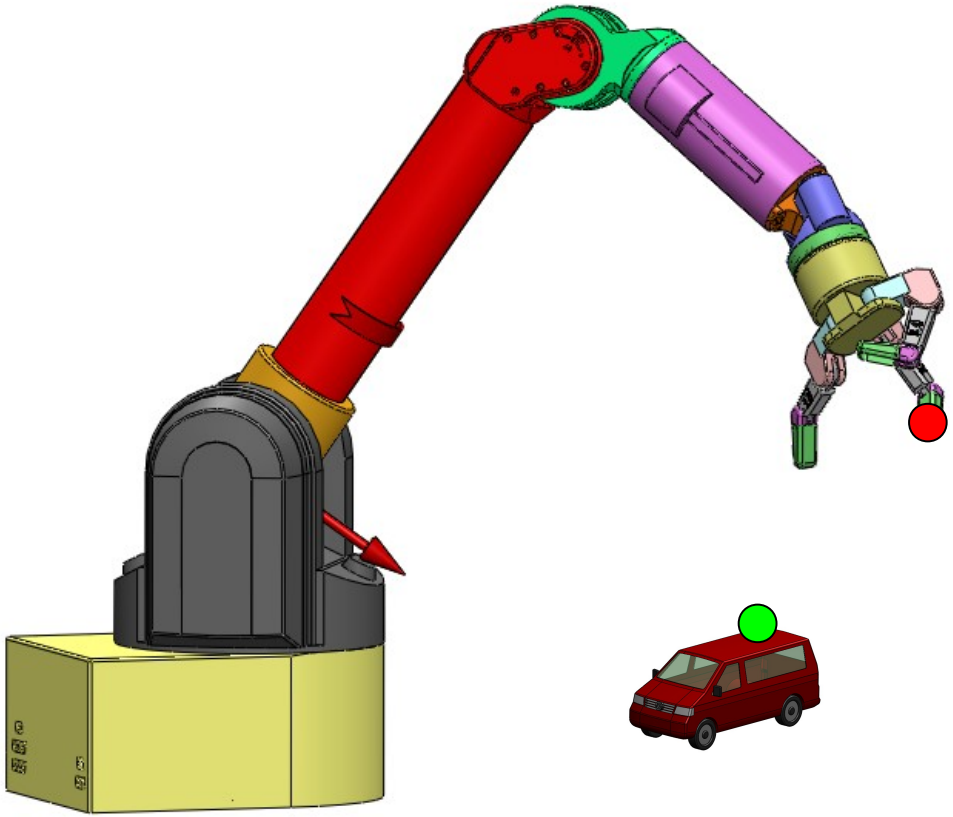

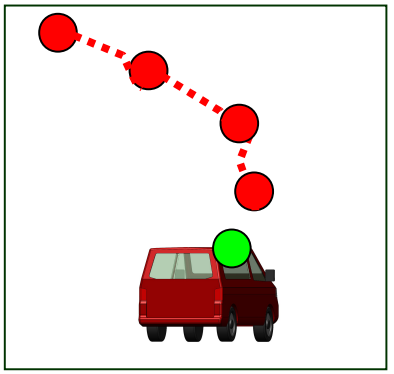

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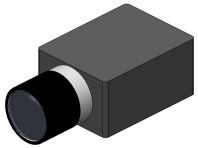

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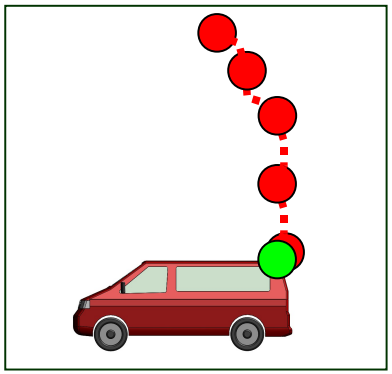

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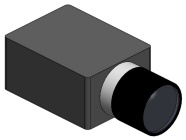

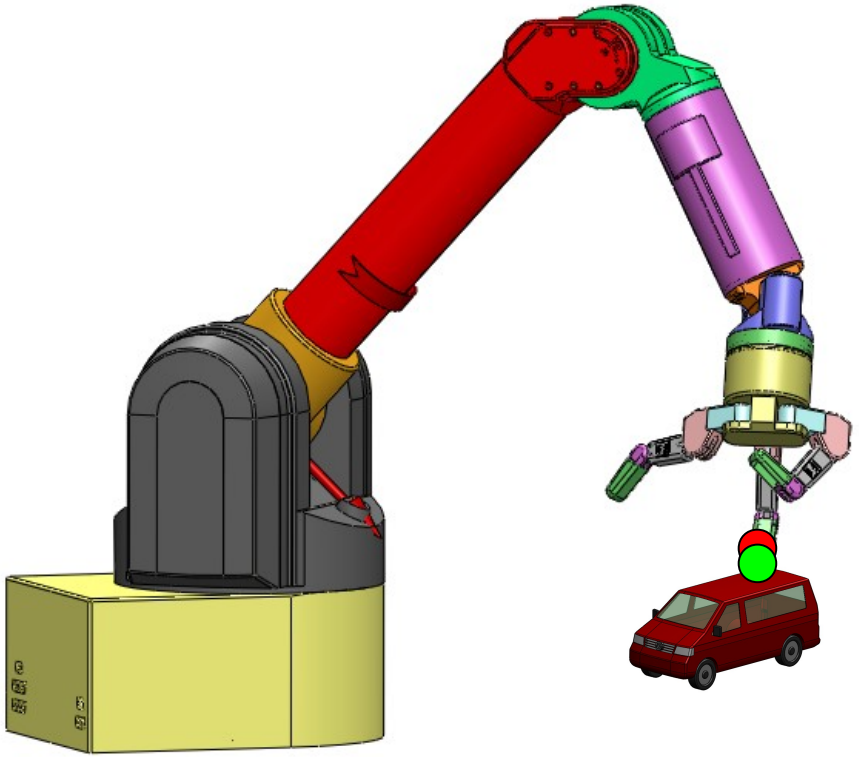

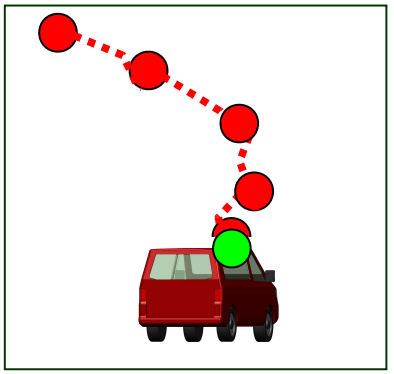

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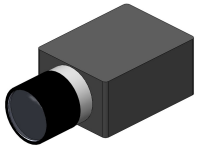


Outline

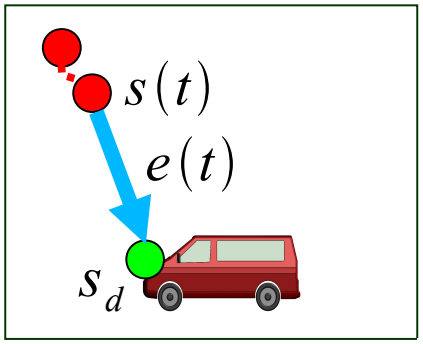
- Problem Definition
- From Vision to Action: Principles
- Image-Based Visual Servoing (IBVS)
- Model-Dependent IBVS
- Model-Free (Uncalibrated) IBVS
  - Broyden Method to Update Jacobian
  - Least-Squares to Estimate Jacobian
- Positioin-Based Visual Servoing (PBVS)
  - PBVS: Frames of Reference
  - PBVS: EKF-Based Pose Tracking
- Summary and Conclusions

Problem Definition

- 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.

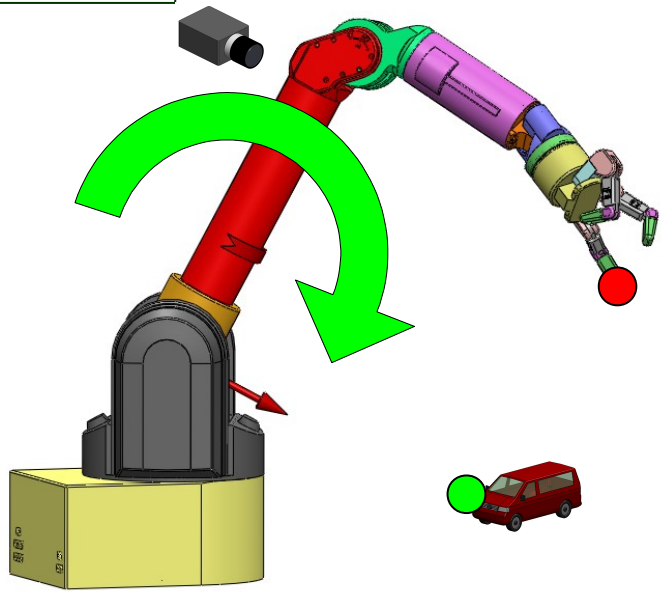
From Vision to Action: Principles



$$e(t) = s(t) - s_d$$

$$\dot{q} = -\lambda J^{+} e(t)$$

Image 1



$$s = F(q)$$

$$\frac{ds}{dt} = \frac{\delta F}{\delta q}\frac{dq}{dt}$$

Image Jacobian
(Interaction Matrix)

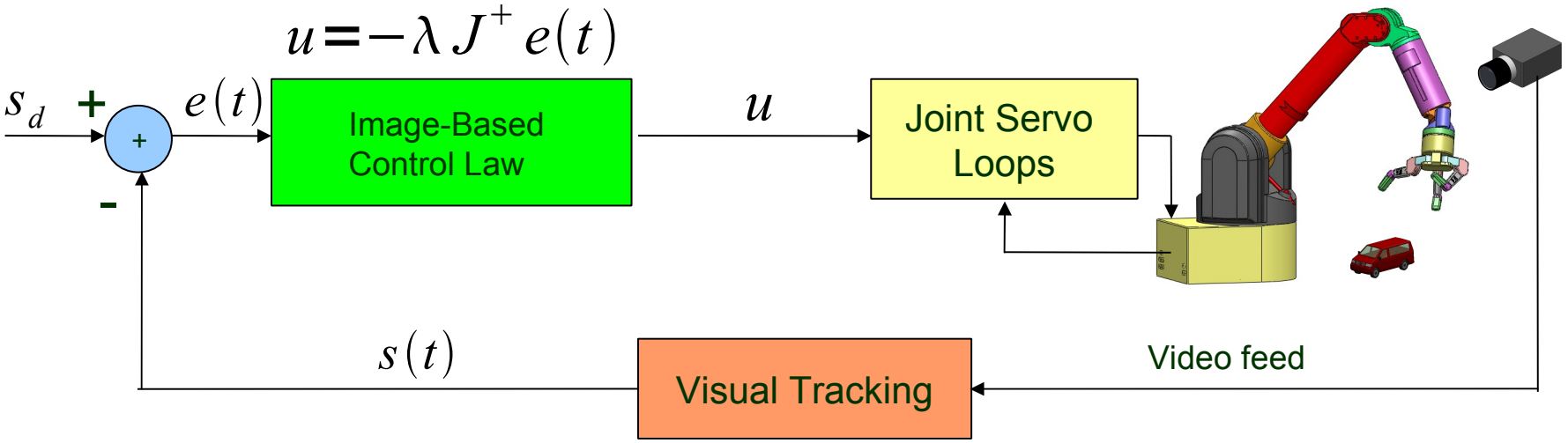
$$J = \frac{\delta F}{\delta q}$$

$$J^{+} = (J^{T} J)^{-1} J^{T}$$

q : Joint values

$s(t)$: image feature

Image-Based Visual Servoing (IBVS)



s_d: Desired image feature

$s(t)$: Visually-tracked image feature

Model-Dependent IBVS

- Analytic form, model-dependent estimation (calibrated)

$$\begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} -f\frac{1}{Z} & 0 & f\frac{u}{Z} & f\frac{uv}{Z} & -\frac{f^2+u^2}{f} & v \\ 0 & -f\frac{1}{Z} & \frac{v}{Z} & \frac{f^2+v^2}{f} & -\frac{uv}{Z} & -u \end{bmatrix} \begin{bmatrix} V \\ \Omega \end{bmatrix}$$

Stability analysis available, but some calibration is necessary. [Espiau '92][Chaumette '98]

- What if analytical form was not available?
  - Numerically estimation the image Jacobian (uncalibrated image-based) [Jagersand '97]
  - [Hosoda '94][Piepmeier '04][Farahmand '07]

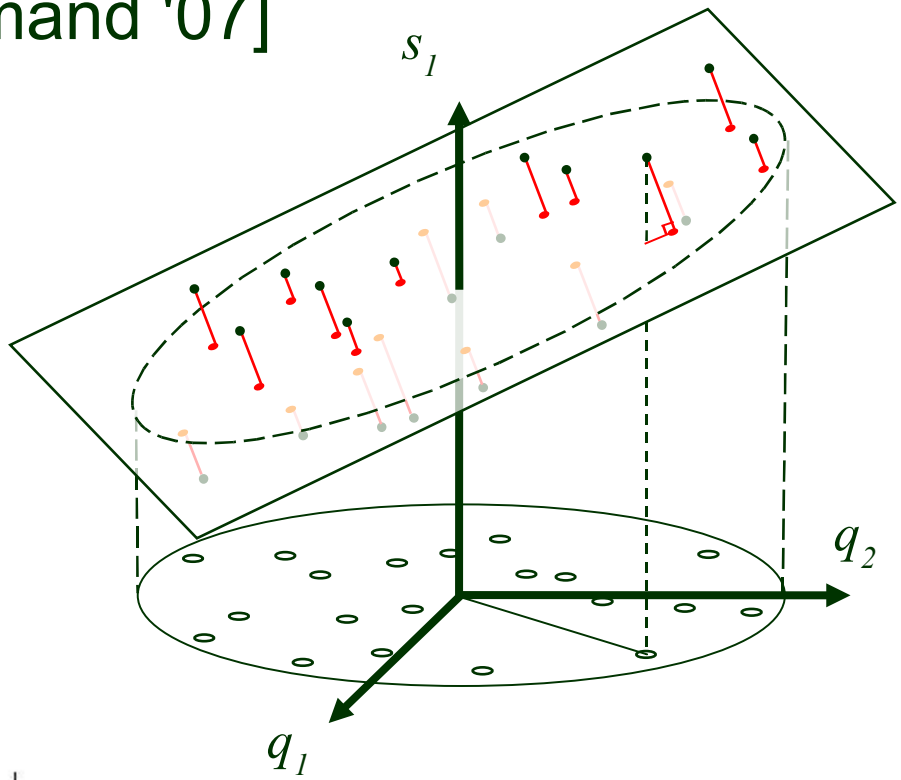
Model-Free (Uncalibrated) IBVS

- Uncalibrated: No prior model information necessary, but standard stability analysis cannot be used.
- Jacobian estimation: Broyden update [Hosoda '94] [Jagersand '97]

$$J(t+1) = J(t) + \alpha \frac{(\Delta s - J(t)\Delta q)\Delta q^T}{\Delta q^T \Delta q}$$

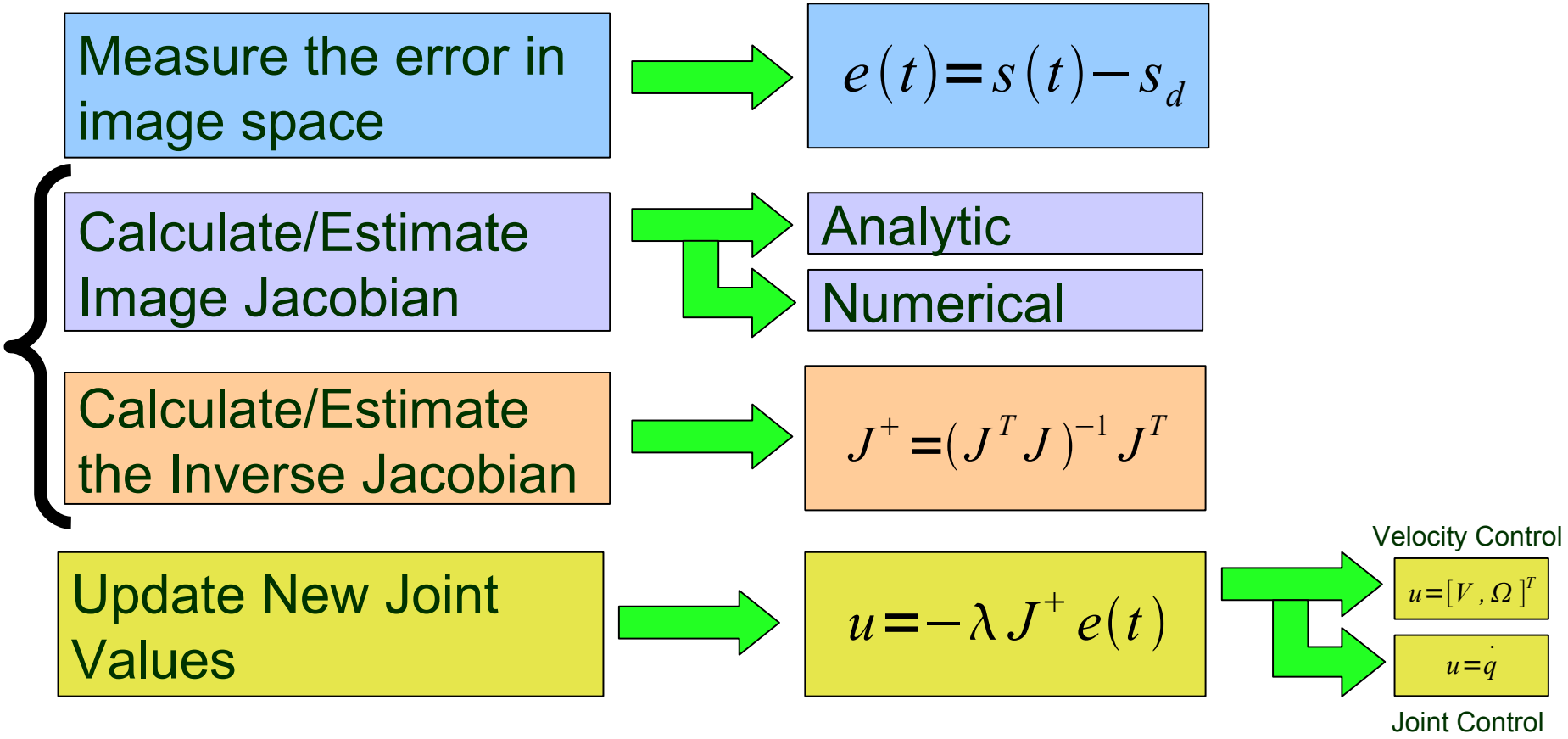
Model-Free (Uncalibrated) IBVS

- Jacobian Estimation: Locally Least Squares (LLS) [Farahmand '07]



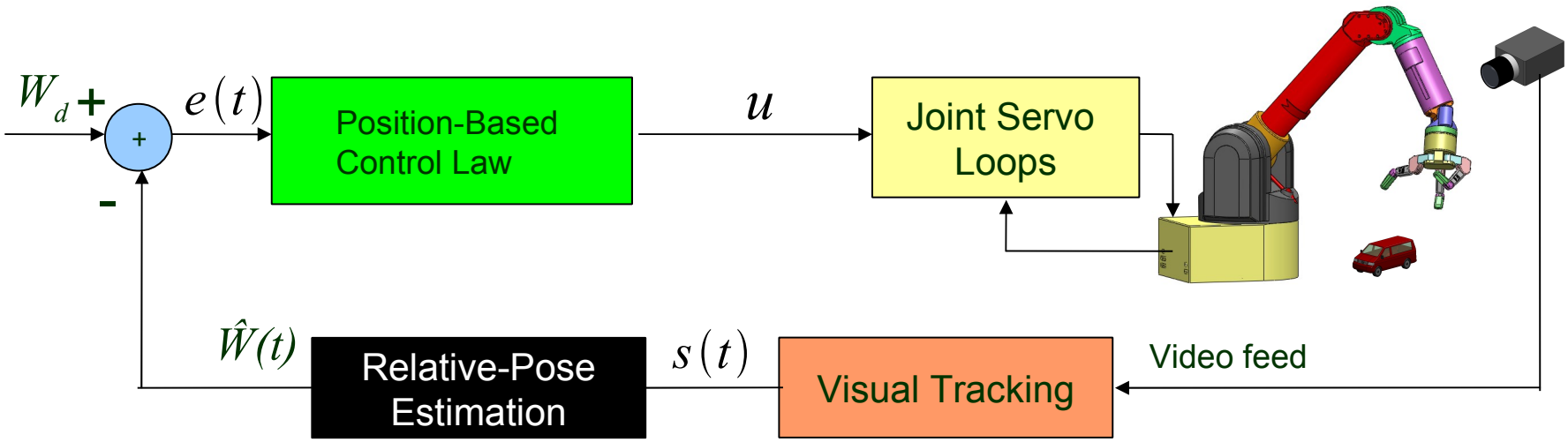
$$\widehat{\mathbf{J}}_{\mathbf{u}}(q)\Big|_{q=q_c} = \arg\min_{\mathbf{J}_{\mathbf{u}}} \sum_{k:\, q_k \in B_r(q_c)} (\Delta s_k - \mathbf{J}_{\mathbf{u}} \Delta q_k)^2$$

Image-Based Control Law



Local asymptoic stability

Position-Based Visual Servoing (PBVS)

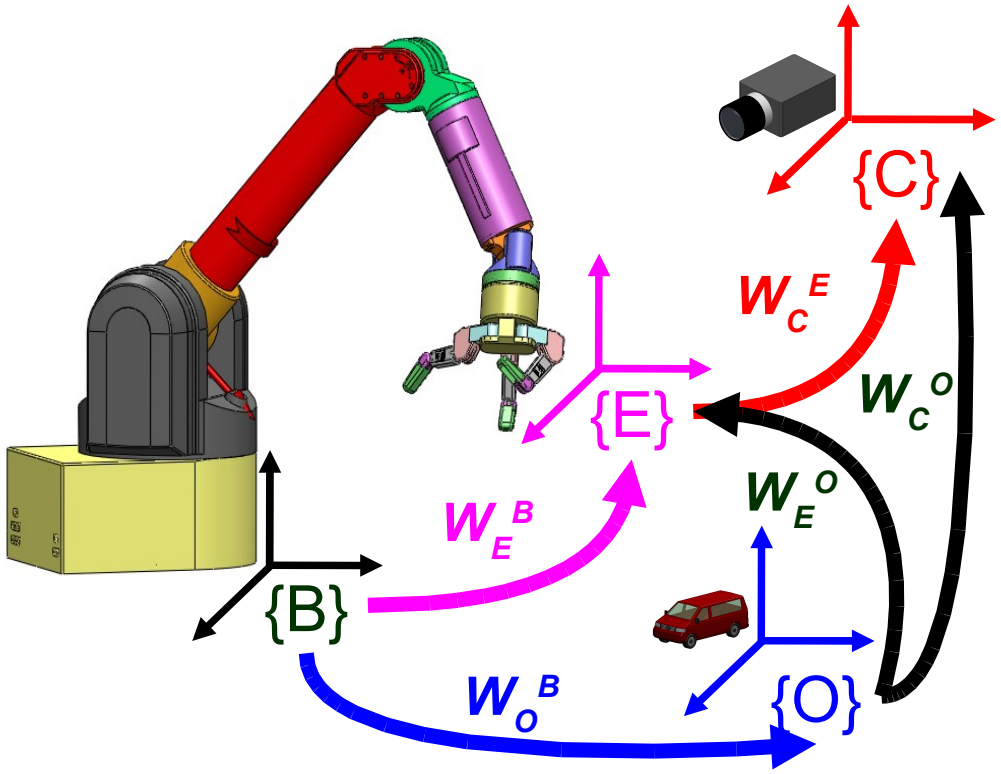


W_d: Desired relative pose (end-effector to object)

$\hat{W}(t)$: Estimated relative pose

$s(t)$: Visually-tracked image feature

Position-Based: Frames



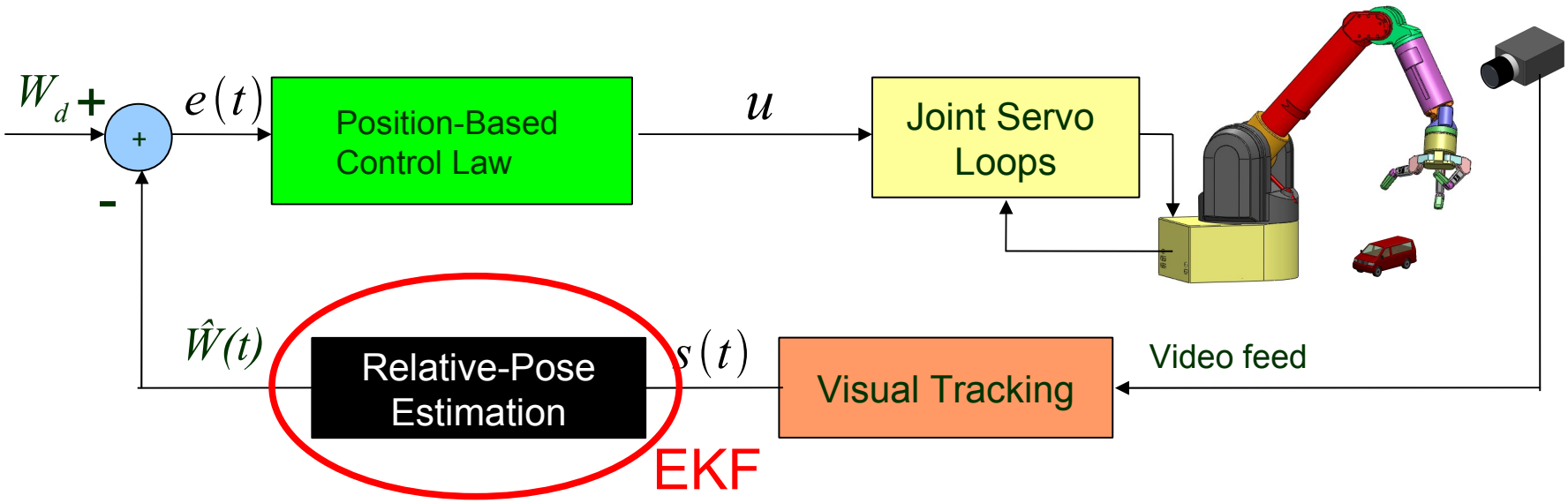
W_E^B: Fwd Kinematics (known)

W_C^E : End-effector to Camera (Calibration required)

W_C^O: Object to Camera (vision algorithm)

W_E^O: Relative Object to End-Effector Pose (Desired, Control)

Position-Based Visual Servoing (PBVS)



W_d: Desired relative pose (end-effector to object)

$\hat{W}(t)$: Estimated relative pose

$s(t)$: Visually-tracked image feature

Position-Based: EKF-Based Pose Tracking

$$\begin{cases} x(k) = A\,x(k-1) + w_k \\ s(k) = G(x(k)) + v_k \end{cases}$$

Process noise

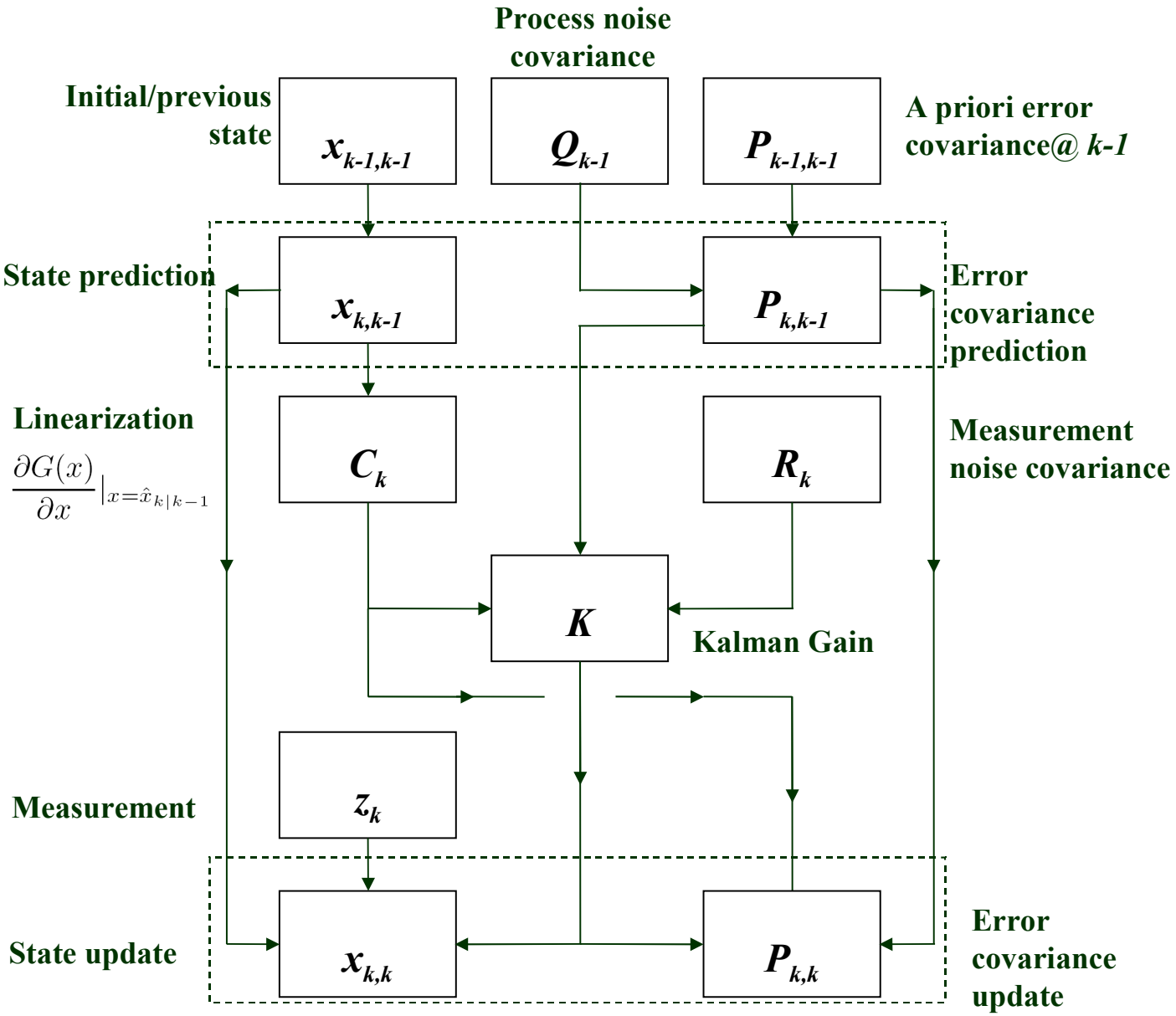
Measurement noise

State variable

$$x = [\, X, \dot{X}, Y, \dot{Y}, Z, \dot{Z}, \psi, \dot{\psi}, \theta, \dot{\theta}, \phi, \dot{\phi} \,]^T$$

Measurement equation (projection) is nonlinear and must be linearized.

$$G(x) = f\left[\frac{X_1^c}{Z_1^c}, \frac{Y_1^c}{Z_1^c}, \frac{X_2^c}{Z_2^c}, \frac{Y_2^c}{Z_2^c}, \frac{X_3^c}{Z_3^c}, \frac{Y_3^c}{Z_3^c}\right]$$


Process noise covariance
Initial/previous state
$x_{k-1,k-1}$
Q_{k-1}
$P_{k-1,k-1}$
A priori error covariance@ k-1
State prediction
$x_{k,k-1}$
$P_{k,k-1}$
Error covariance prediction
Linearization
$\frac{\partial G(x)}{\partial x}|_{x=\hat{x}_{k|k-1}}$
C_k
R_k
Measurement noise covariance
K
Kalman Gain
Measurement
z_k
State update
$x_{k,k}$
$P_{k,k}$
Error covariance update

Position-Based: Summary

- Real-time relative pose estimation
- Extended Kalman Filter to solve the nonlinear relative pose equations [Wilson '96].
- Pros:
  - Global asymptotic stability
  - Robustness achieved with low measurement noise and accurate calibration parameters.
- Cons:
  - Requires accurate calibration.
  - Performance and the convergence of pose estimates are highly *sensitive* to EKF parameters.

Summary & Conclusions

- Image-Based [Espiau '92][Jagersand '97]:
  - Desired image features seen from camera
  - Control law entirely based on image features
- Position-Based [Wilson '96]:
  - Cameras as 3D sensors
  - Real-time pose estimation + robot's world-space (Cartesian) controller
- Hybrid (2-1/2D) [Malis '99]:
  - Depth information is added to image data to increase stability
  - Partial 3D pose estimation: position control to control linear velocity, rotation control to control rotational velocity

Summary & Conclusions

- Different control laws have different applications.
- Position-Based: Structured environments, such as factory automation. CAD model of object must be known.
- Model-Dependent Image-Based: CAD model of object is not available, but analytic form of image Jacobian is available.
- Model-Free (Uncalibrated) Image-Based:
  - No model information necessary. Ideal for systems without model information (flexible limbs, complex feature forms, etc.)
  - Model Must be numerically *estimated* (or learned) if model is not known.

Some References

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• M. Jägersand, O. Fuentes, R. Nelson, "Experimental Evaluation of Uncalibrated Visual Servoing for Precision Manipulation," Proc. IEEE Intl. Conference on Robotics and Automation (ICRA), pp. 2874-2880, 20-25 Apr. 1997.

• F. Chaumette, "Potential problems of stability and convergence in image-based and position-based visual servoing," The Confluence of Vision and Control, LNCS Series, No 237, Springer-Verlag, 1998, p. 66-78.

Thank you!

Typical Features & Tasks in Visual Servoing

- Image Features
  - Geometric primitives
    - Points
    - Lines
  - Higher order image moments
  - Shapes
- Visual Tasks
  - Point-to-point alignment
  - Point-to-line alignment
  - Shape alignment

Classification of Visual Servoing Systems

- Hand/eye configuration:
  - Static camers: eye-to-hand
  - Dynamic cameras: eye-in-hand
- Number of cameras:
  - Monocular, binocular, etc
- Model information
  - Model-free (uncalibrated), model-dependent
- Control law
  - Position-based, image-based, hybrid