



Introduction to Vision-Based Motion Control of Robots

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INFORMATICS



CORE

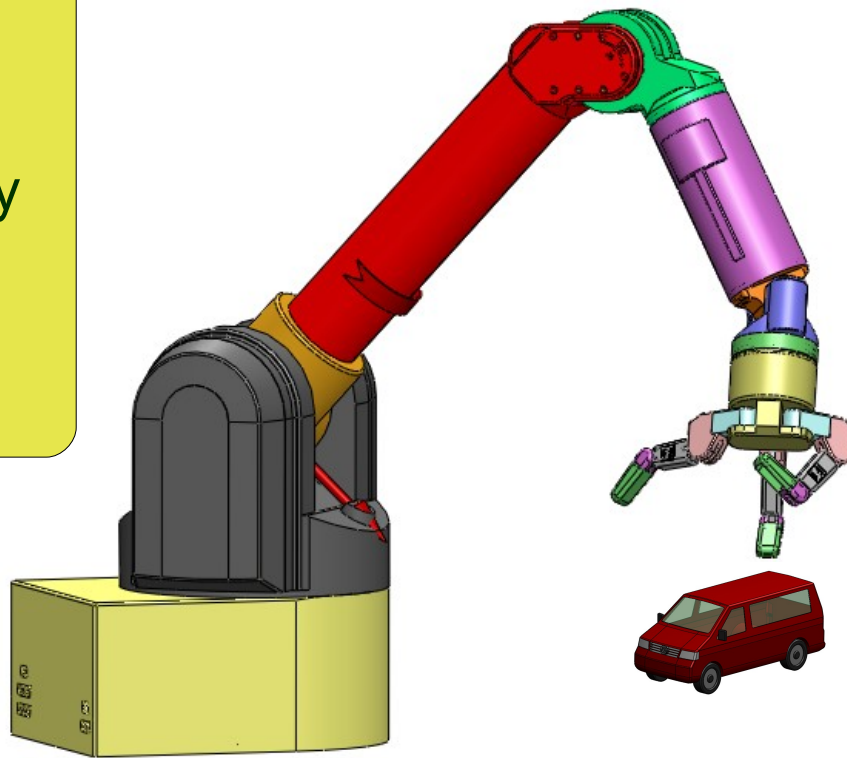
CIRCLE OF RESEARCH EXCELLENCE

Vision-Based Control

Do something
useful, robot!

Pick up the toy
car!

Use cameras.



Vision-Based Control

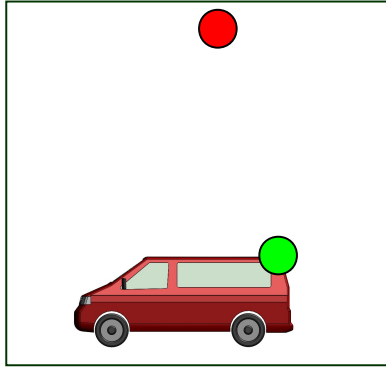


Image 1

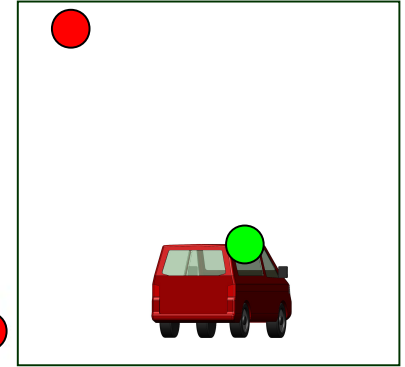
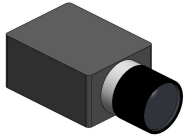
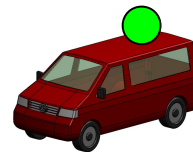
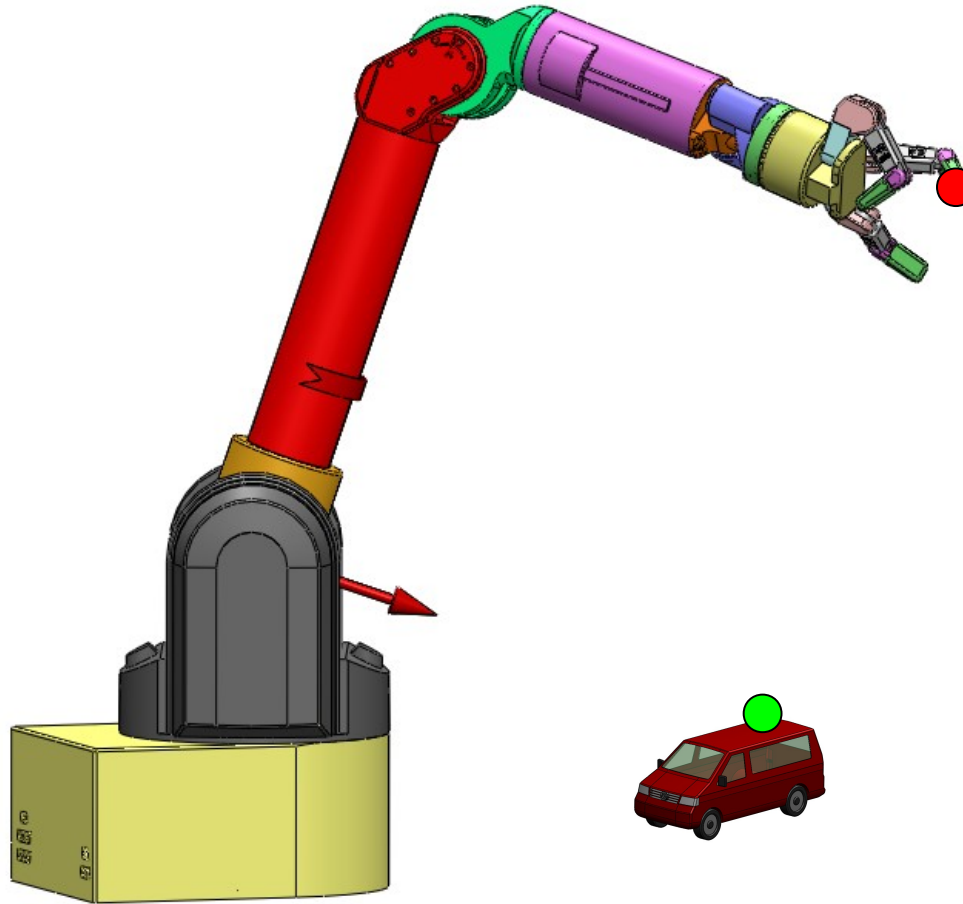
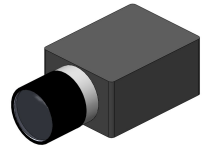


Image 2



Vision-Based Control

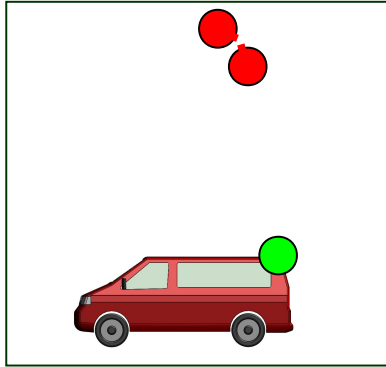


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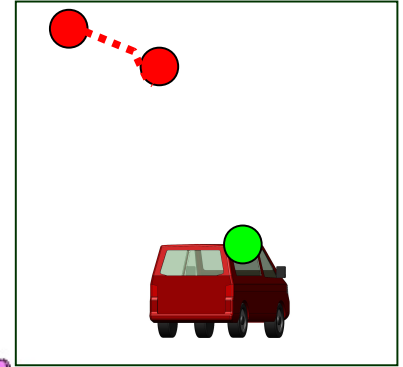
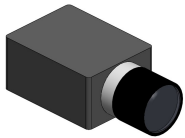
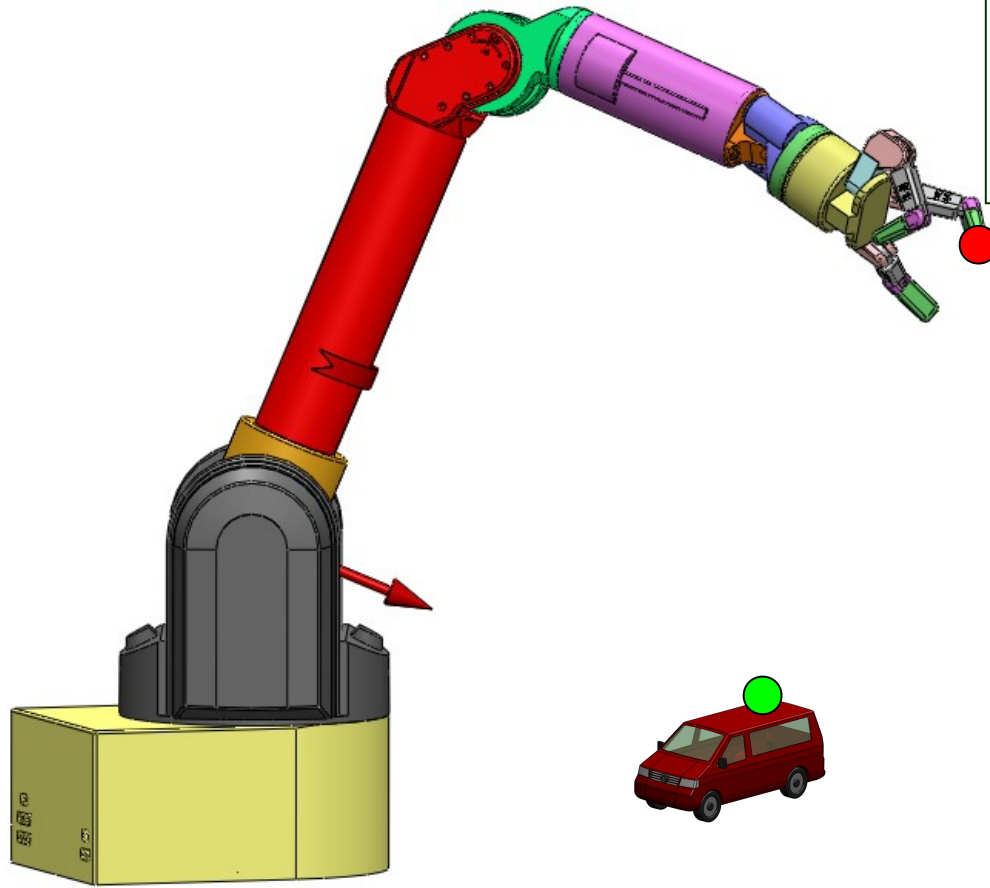
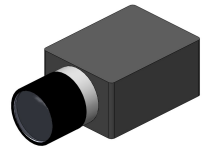


Image 2



Vision-Based Control

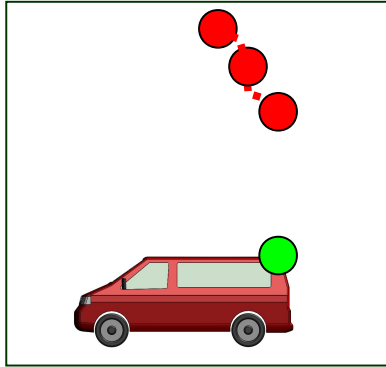


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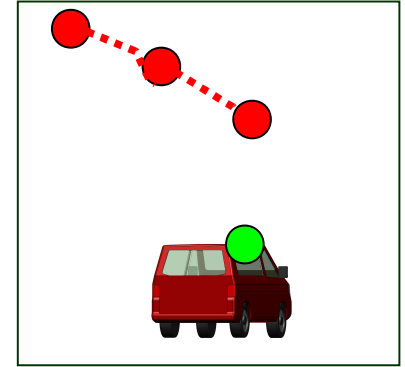
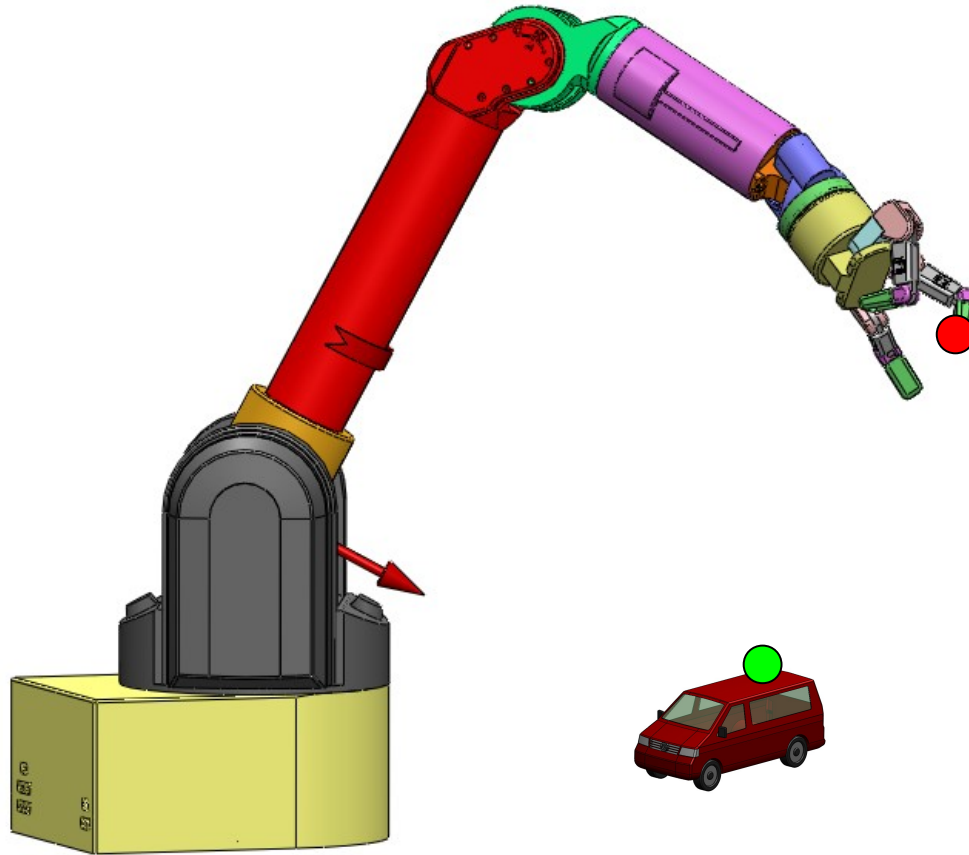
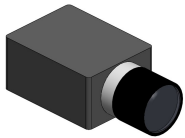
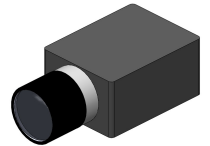


Image 2



Vision-Based Control

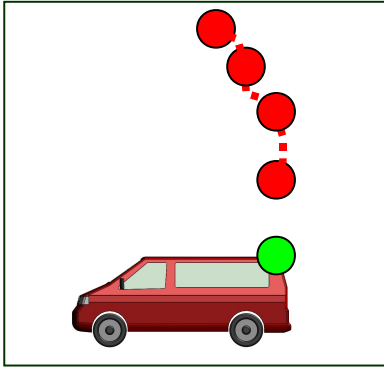


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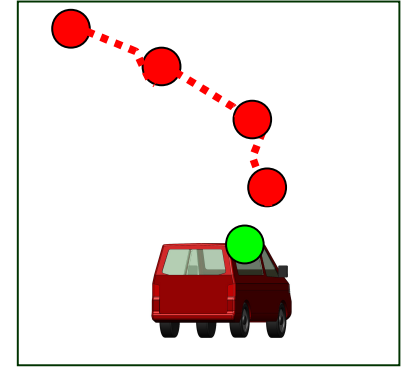
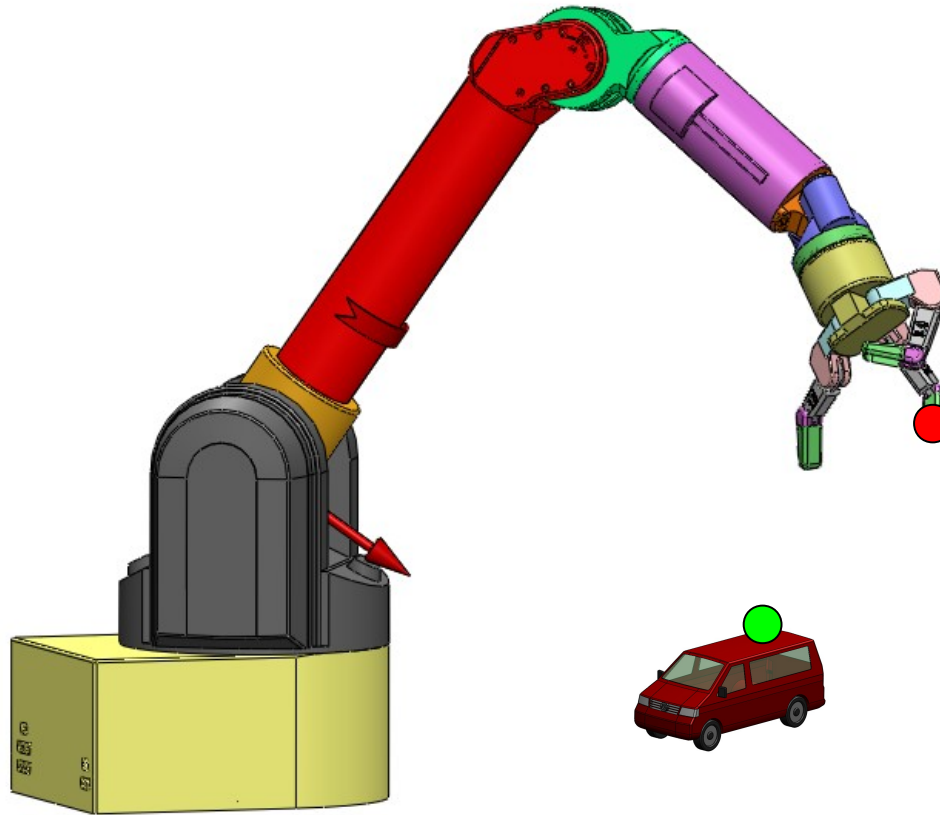
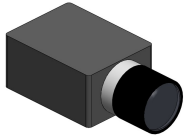
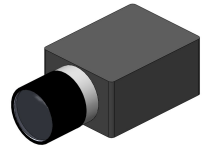


Image 2



Vision-Based Control

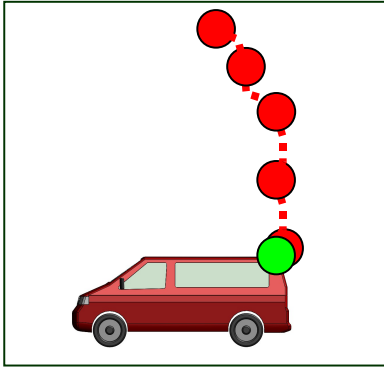


Image 1

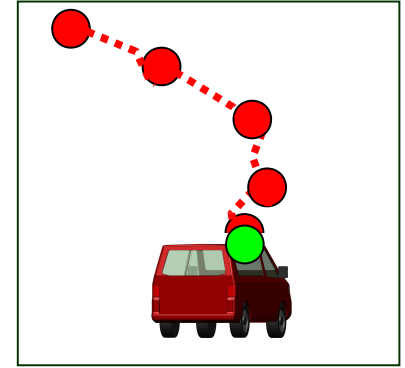
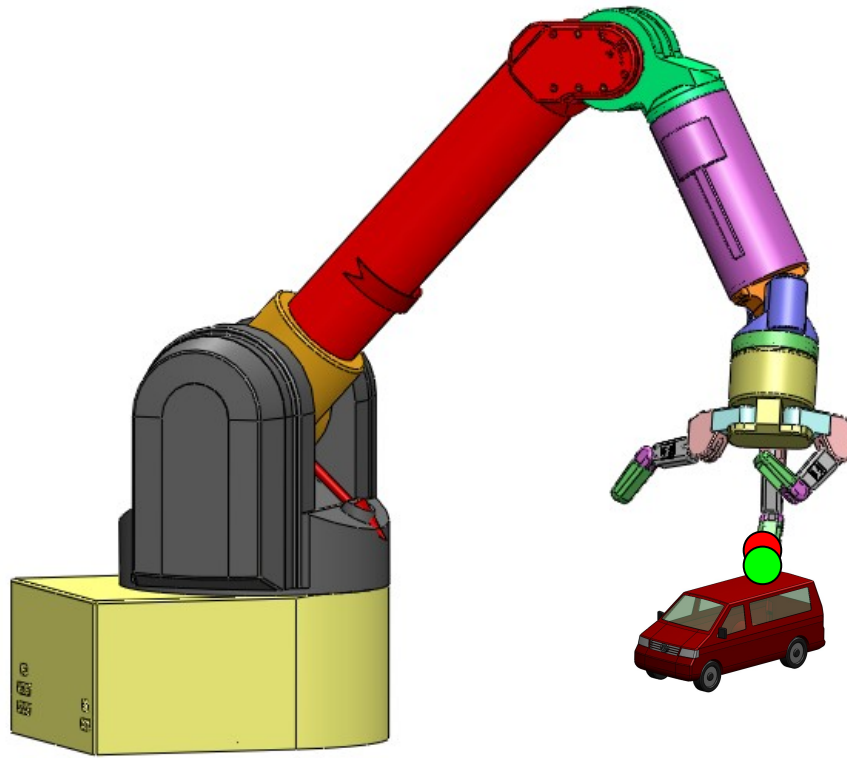
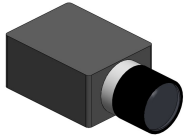
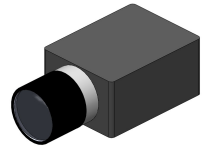


Image 2



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
- Position-Based Visual Servoing (PBVS)
 - PBVS: Frames of Reference
 - PBVS: EKF-Based Pose Tracking
- Summary and Conclusions

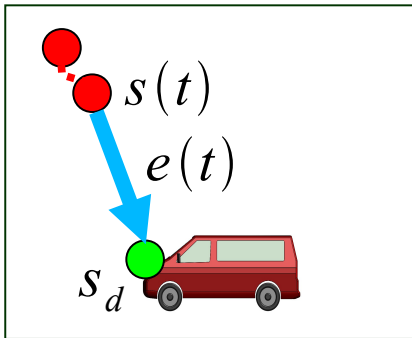


Problem Definition

- 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.



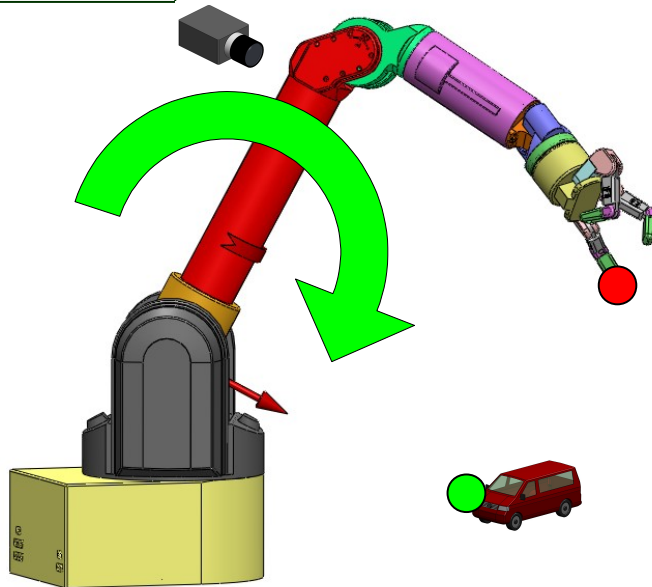
From Vision to Action: Principles



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

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

Image 1



q : Joint values

$s(t)$: image feature

$$s = F(q)$$

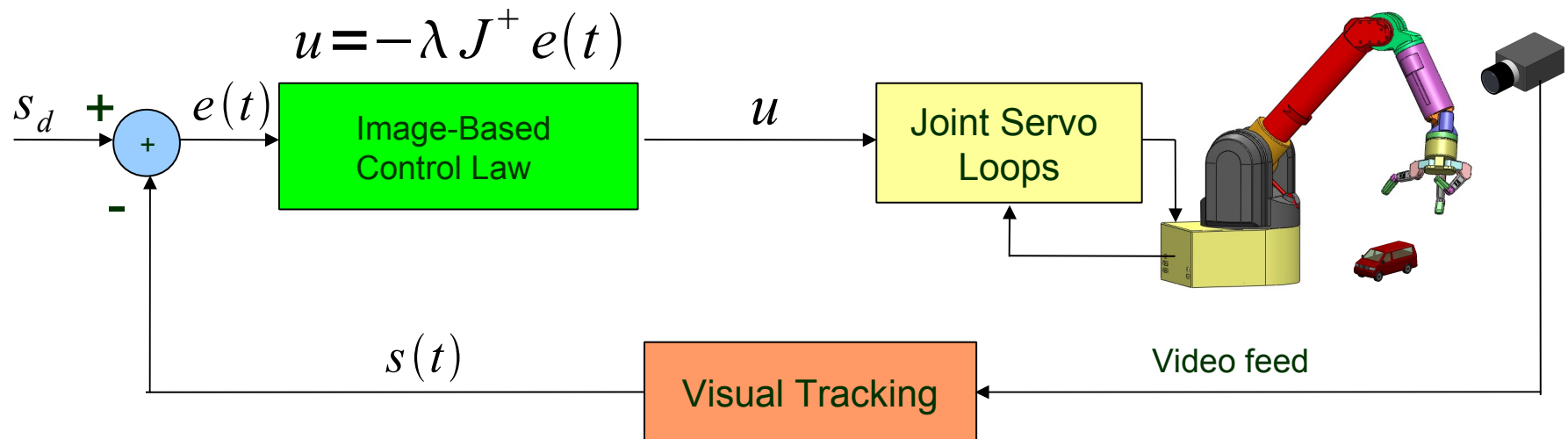
$$\frac{ds}{dt} = \frac{\delta F}{\delta q} \frac{dq}{dt}$$

Image Jacobian
(Interaction Matrix)

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

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

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

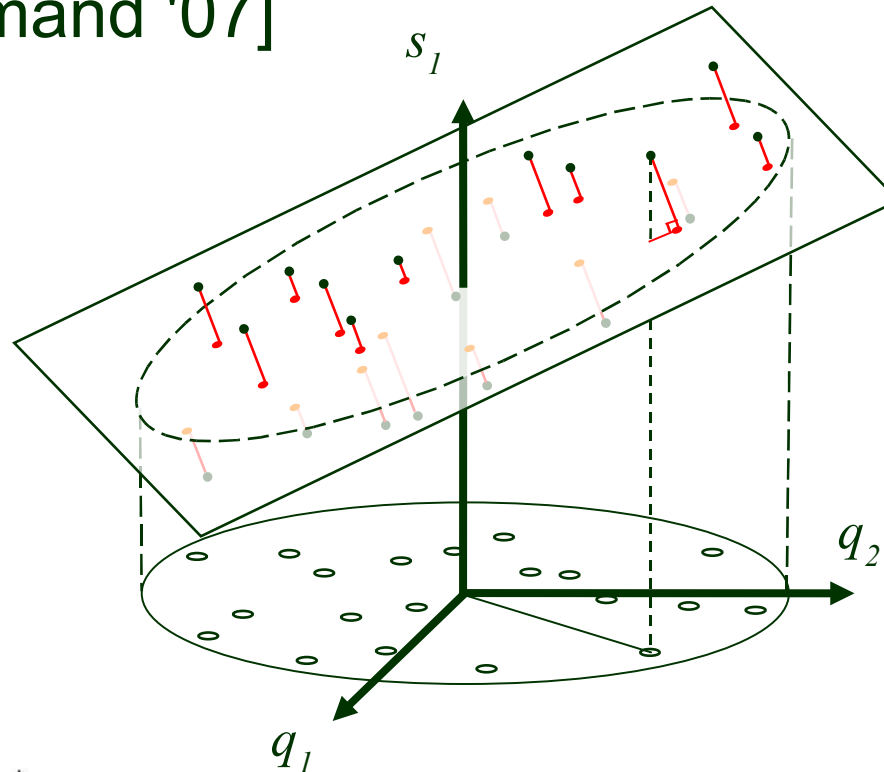
- Uncalibrated: No prior model information necessary, but standard stability analysis cannot be used.
- Jacobian estimation: Broyden update [Hosoda '94] [Jagersand '97]

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



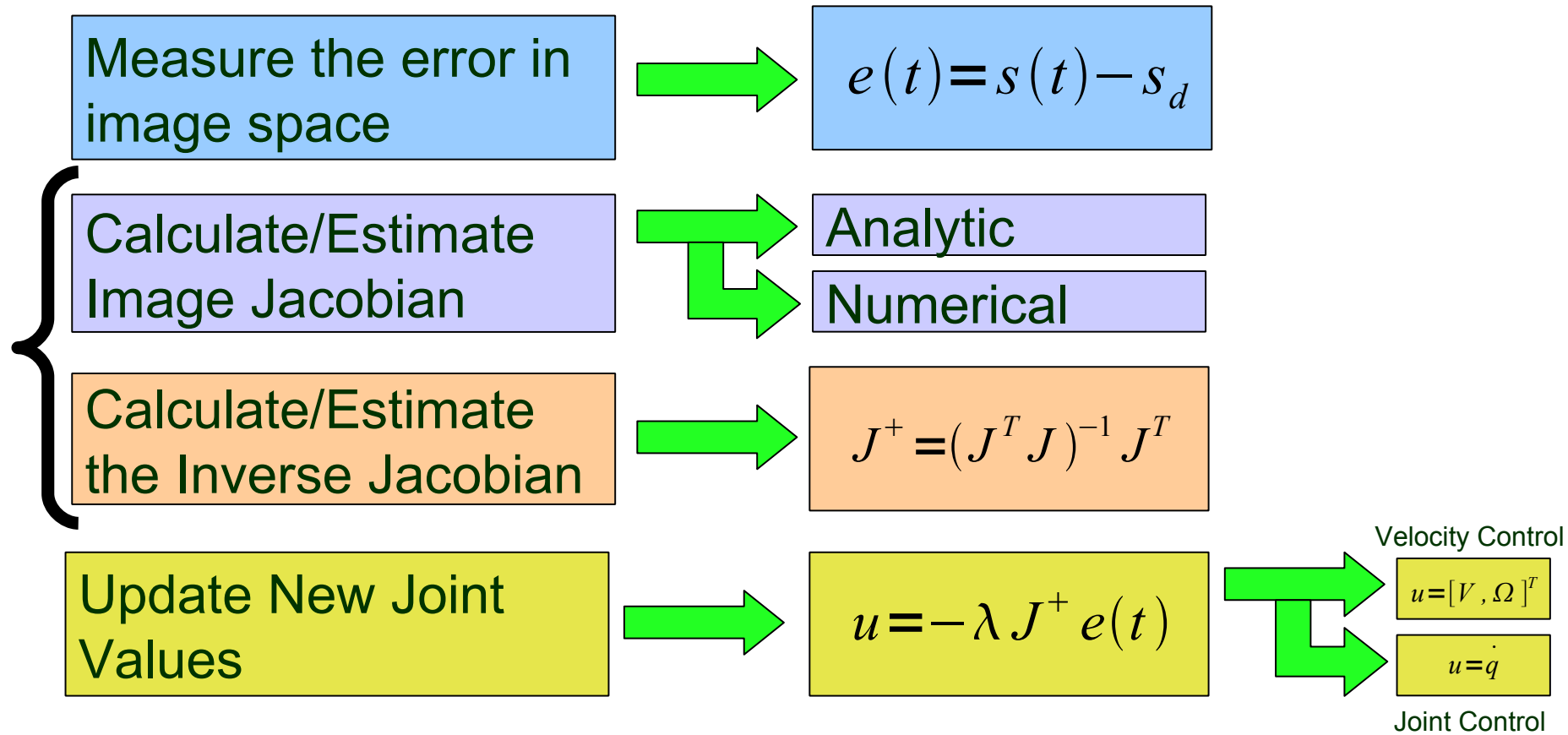
Model-Free (Uncalibrated) IBVS

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



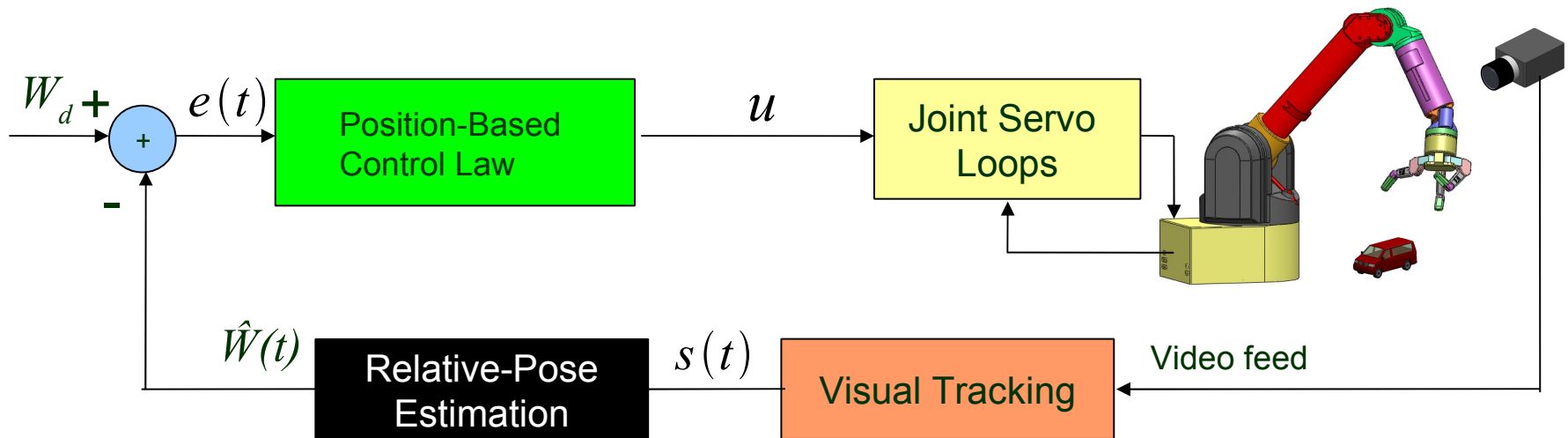
$$\hat{\mathbf{J}}_{\mathbf{u}}(\mathbf{q}) \Big|_{\mathbf{q}=\mathbf{q}_c} = \arg \min_{\mathbf{J}_{\mathbf{u}}} \sum_{k: \mathbf{q}_k \in B_r(\mathbf{q}_c)} (\Delta s_k - \mathbf{J}_{\mathbf{u}} \Delta \mathbf{q}_k)^2$$

Image-Based Control Law



Local asymptotic stability

Position-Based Visual Servoing (PBVS)

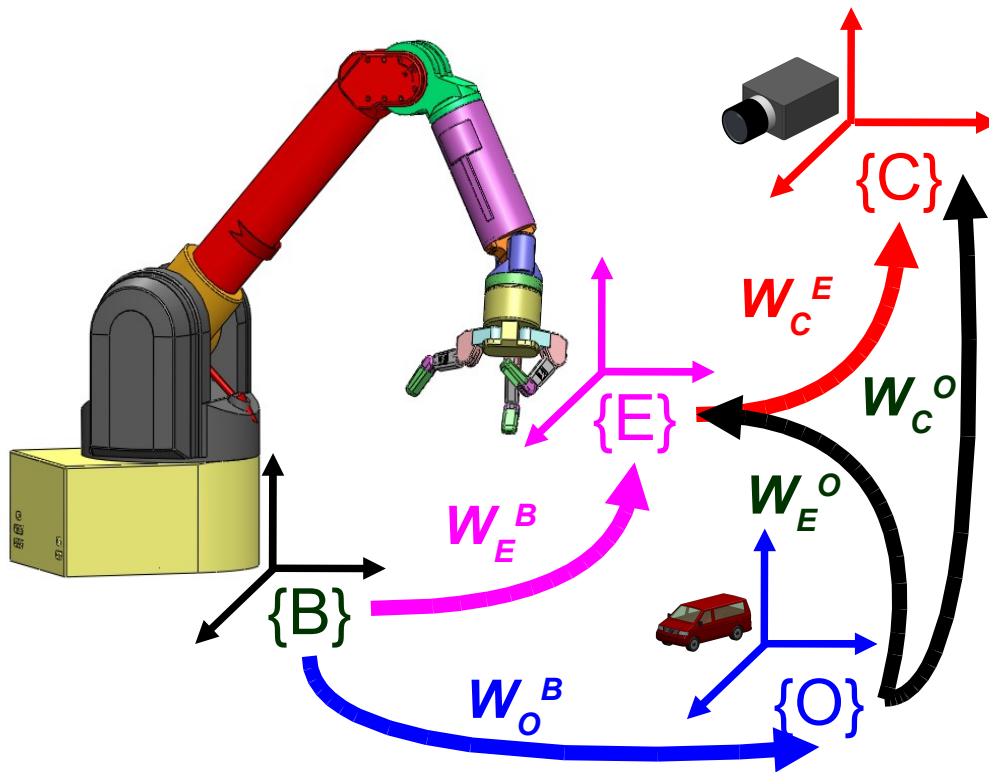


W_d : Desired relative pose (end-effector to object)

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

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

Position-Based: Frames



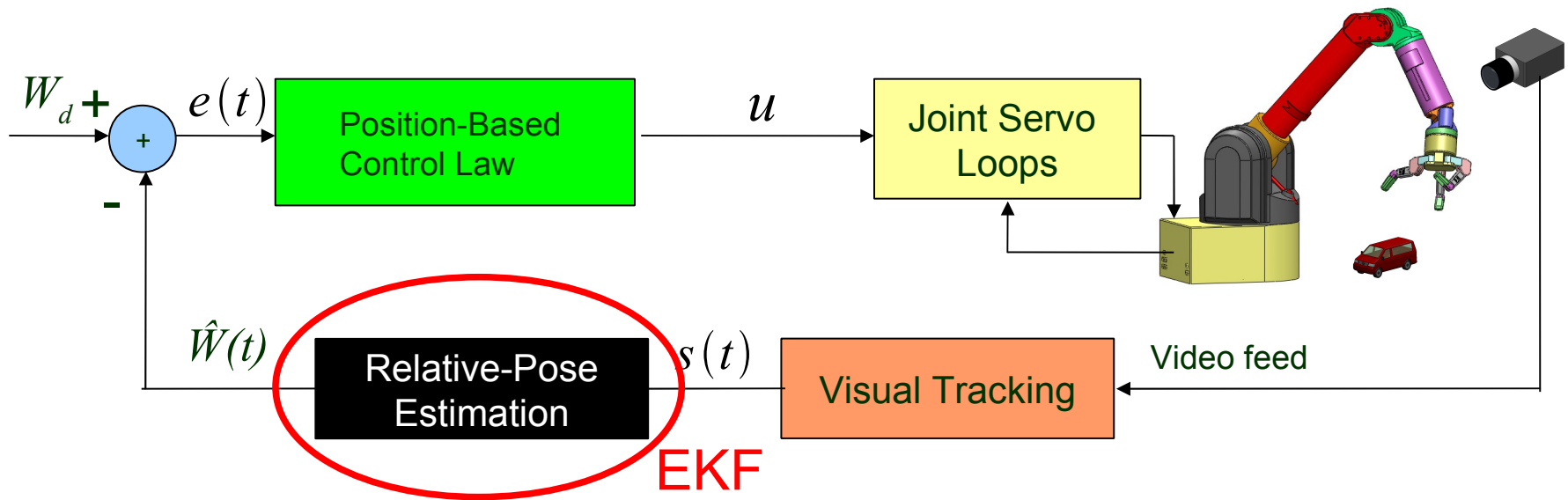
W_E^B : Fwd Kinematics (known)

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

$$\begin{cases} x(k) = Ax(k-1) + w_k & \text{Process noise} \\ s(k) = G(x(k)) + v_k & \text{Measurement noise} \end{cases}$$

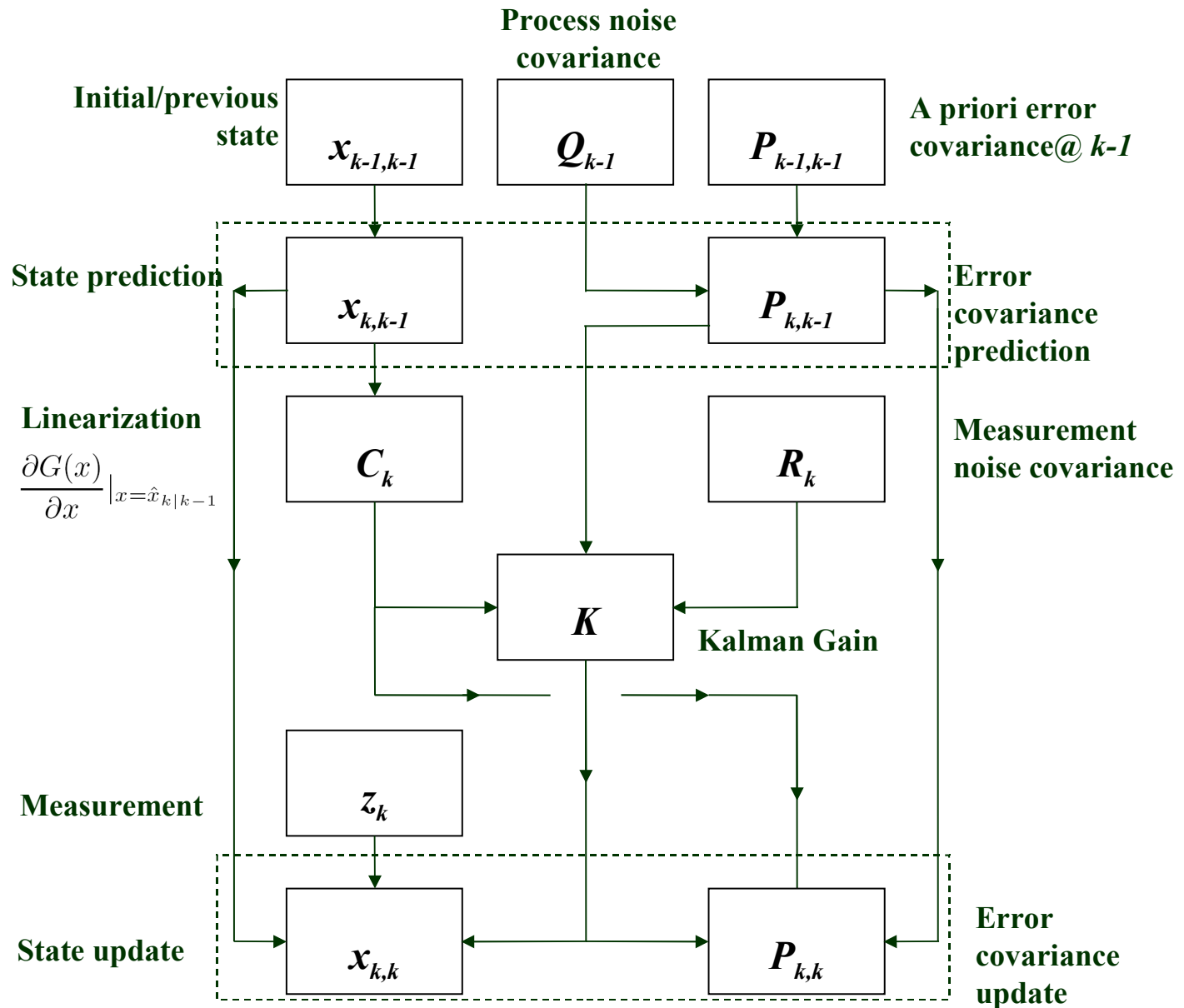
State variable

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

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

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





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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- E. Malis, F. Chaumette, S. Boudet, "2 1/2 D visual servoing," IEEE Trans. on Robotics and Automation, April 1999, vol. 15, no. 2, p. 238-250.
- 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 cameras: 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

