Cooperative Control with Visual Feedback System

Fujita Laboratory
FL07-25-2
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Outline

1. Visual Feedback
2. Experiment
3. Future Work

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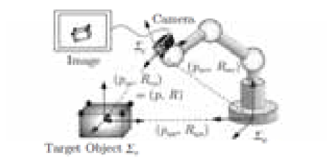
Visual Feedback

$$p_{wo} = p_{wc} + R_{wc} p$$
$$R_{wo} = R_{wc} R$$
$$\downarrow$$
$$p = R_{wc}{}^T (p_{wo} - p_{wc})$$
$$R = R_{wc}{}^T R_{wo}$$



Σ_w : world frame
Σ_c : camera frame
Σ_o : object frame

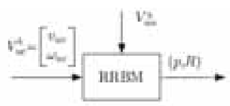
$$\dot{p} = \dot{R}_{wc}{}^T (p_{wo} - p_{wc}) + R_{wc}{}^T (\dot{p}_{wo} - \dot{p}_{wc})$$
$$\dot{R} = \dot{R}_{wc}{}^T R_{wo} + R_{wc}{}^T \dot{R}_{wo}$$

RRBM(Relative Rigid Body Motion)

$$\begin{aligned}\dot{p} &= \dot{R}_{wc}{}^T (p_{wo} - p_{wc}) + R_{wc}{}^T (\dot{p}_{wo} - \dot{p}_{wc}) \\ &= -R_{wc}{}^T \dot{R}_{wc} R_{wc}{}^T (p_{wo} - p_{wc}) + R_{wc}{}^T (R_{wo} v_{wo} - R_{wc} v_{wc}) \\ &= -v_{wc} + \hat{p}\omega_{wc} + R v_{wo}\end{aligned}$$

$$\begin{aligned}\dot{R} &= \dot{R}_{wc}{}^T R_{wo} + R_{wc}{}^T \dot{R}_{wo} \\ &= -R_{wc}{}^T (R_{wc}\hat{\omega}_{wc}) R_{wc}{}^T R_{wo} + R_{wc}{}^T (R_{wo}\hat{\omega}_{wo}) \\ &= -\hat{\omega}_{wc} + R\hat{\omega}_{wo}\end{aligned}$$

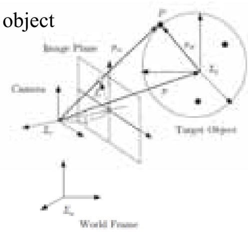
$$\begin{bmatrix} R^T \dot{p} \\ (R^T \dot{R})^{\vee} \end{bmatrix} = -\begin{bmatrix} R^T & -R^T \hat{p} \\ 0 & R^T \end{bmatrix}\begin{bmatrix} v_{wc} \\ \omega_{wc} \end{bmatrix} + \begin{bmatrix} v_{wo} \\ \omega_{wo} \end{bmatrix}$$:RRBM

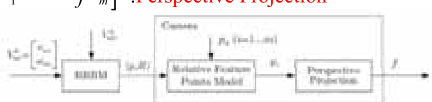


Perspective Projection

Consider m（≧4）points on the target object

$$p_{ci} = [x_{ci} \quad y_{ci} \quad z_{ci}]^T$$
$$= Rp_{oi} + p$$
$$p_{oi} = [x_{oi} \quad y_{oi} \quad z_{oi}]^T$$
$$p_c = [p^T{}_{c1} \quad \cdots \quad p^T{}_{cm}]^T$$
$$f_i = \frac{\lambda}{z_{ci}}\begin{bmatrix} x_{ci} \\ y_{ci} \end{bmatrix}$$
$$f = [f^T{}_1 \quad \cdots \quad f^T{}_m]^T$$:Perspective Projection





EsRRBM(Estimated Relative Rigid Body Motion)

Define estimated value of (p, R) as $(\bar{p}, \bar{R})$

$$\begin{bmatrix} \bar{R}^T \dot{\bar{p}} \\ (\bar{R}^T \dot{\bar{R}})^\vee \end{bmatrix} = -\begin{bmatrix} \bar{R}^T & -\bar{R}^T \hat{\bar{p}} \\ 0 & \bar{R}^T \end{bmatrix} \begin{bmatrix} v_{wc} \\ \omega_{wc} \end{bmatrix} + u_e \quad \text{:EsRRBM}$$

$$\bar{p}_{ci} = \begin{bmatrix} \bar{x}_{ci} & \bar{y}_{ci} & \bar{z}_{ci} \end{bmatrix}^T = \bar{R} p_{oi} + \bar{p}$$

$$\bar{p}_c = \begin{bmatrix} \bar{p}^T{}_{c1} & \cdots & \bar{p}^T{}_{cm} \end{bmatrix}^T$$

$$\bar{f}_i = \frac{\lambda}{\bar{z}_{ci}} \begin{bmatrix} \bar{x}_{ci} \\ \bar{y}_{ci} \end{bmatrix} \qquad \bar{f} = \begin{bmatrix} \bar{f}^T{}_1 & \cdots & \bar{f}^T{}_m \end{bmatrix}^T$$

Estimated Error

$$p_{ee} = \bar{R}^T (p - \bar{p})$$
$$R_{ee} = \bar{R}^T R$$

$$e_{ee} = \begin{bmatrix} p_{ee} \\ e_R(R_{ee}) \end{bmatrix} = \begin{bmatrix} \bar{R}^T (p - \bar{p}) \\ e_R(\bar{R}^T R) \end{bmatrix} \quad \text{:estimated error vector}$$

$$e_R(R_{ee}) = \frac{1}{2}(R_{ee} - R_{ee}{}^T)^\vee$$

Image Jcobian

$$f_i - \bar{f}_i = \begin{bmatrix} \frac{\lambda}{\bar{z}_{ci}} & 0 & -\frac{\lambda \bar{x}_{ci}}{\bar{z}^2{}_{ci}} \\ 0 & \frac{\lambda}{\bar{z}_{ci}} & -\frac{\lambda \bar{x}_{ci}}{\bar{z}^2{}_{ci}} \end{bmatrix} (p_{ci} - \bar{p}_{ci})$$

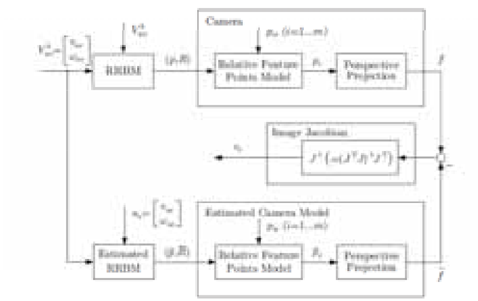
$$\approx \begin{bmatrix} \frac{\lambda}{\bar{z}_{ci}} & 0 & -\frac{\lambda \bar{x}_{ci}}{\bar{z}^2{}_{ci}} \\ 0 & \frac{\lambda}{\bar{z}_{ci}} & -\frac{\lambda \bar{x}_{ci}}{\bar{z}^2{}_{ci}} \end{bmatrix} \begin{bmatrix} I & -(\bar{R} p_{oi})^\wedge \end{bmatrix} \begin{bmatrix} \bar{R} & 0 \\ 0 & \bar{R} \end{bmatrix} \begin{bmatrix} p_{ee} \\ e_R(R_{ee}) \end{bmatrix} = J_i \begin{bmatrix} \bar{R} & 0 \\ 0 & \bar{R} \end{bmatrix} \begin{bmatrix} p_{ee} \\ e_R(R_{ee}) \end{bmatrix}$$

$$f_i - \bar{f}_i = \begin{bmatrix} f_1 - \bar{f}_1 \\ \vdots \\ f_m - \bar{f}_m \end{bmatrix} = \begin{bmatrix} J_1 \\ \vdots \\ J_m \end{bmatrix} \begin{bmatrix} \bar{R} & 0 \\ 0 & \bar{R} \end{bmatrix} \begin{bmatrix} p_{ee} \\ e_R(R_{ee}) \end{bmatrix} = J \begin{bmatrix} p_{ee} \\ e_R(R_{ee}) \end{bmatrix}$$

J :Image Jacobian

$$\begin{bmatrix} p_{ee} \\ e_R(R_{ee}) \end{bmatrix} = J^\dagger (f - \bar{f})$$

Image Jacobian



Estimated Error System

$$\dot{p}_{ee} = \bar{R}^T(\dot{p} - \dot{\bar{p}}) - \bar{R}^T \dot{\bar{R}} \bar{R}^T (p - \bar{p})$$
$$= R_{ee} v_{wo} - v_e + \hat{p}_{ee} \omega_e$$
$$= \begin{bmatrix} -I & \hat{p}_{ee} \end{bmatrix} u_e + \begin{bmatrix} R_{ee} & 0 \end{bmatrix} V^b_{wo}$$

$$\dot{R}_{ee} = \dot{\bar{R}}^T R - \bar{R}^T \dot{R}$$
$$= -(-\bar{R}^T \omega_{wc} + \omega_e)^\wedge \bar{R}^T R + \bar{R}^T R (-\bar{R}^T \omega_{wc} + \omega_{wo})^\wedge$$
$$= \bar{R}^T \hat{\omega}_{wc} R - \hat{\omega}_e R_{ee} - R_{ee} R^T \hat{\omega}_{wc} R + R_{ee} \hat{\omega}_{wo}$$

$$\begin{bmatrix} R_{ee}{}^T \dot{p}_{ee} \\ (R_{ee}^T \dot{R}_{ee})^\vee \end{bmatrix} = -\begin{bmatrix} R_{ee}{}^T & -R_{ee}{}^T \hat{p}_{ee} \\ 0 & R_{ee}{}^T \end{bmatrix} u_e + V^b_{wo} \text{:Estimated Error System}$$

Estimated Error System satisfies Passivity.

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