Passivity-based Visual Motion Observer with PI Estimator

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FL11-14-2

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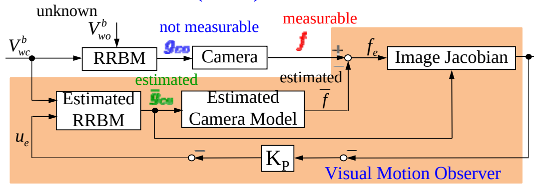
Outline

- Introduction
- Simulation
  - Setting
  - Position
  - Orientation
- Experiment
  - Experimental Environment
  - Position
  - Orientation
- Conclusion and Future Works

Introduction

Visual Motion Observer (VMO)



The visual measurement error (f_e) is computed by image information (f) and estimated image information ($\bar{f}$)

↓ Image Jacobian

The estimation error (e_e) is computed , and is fed back

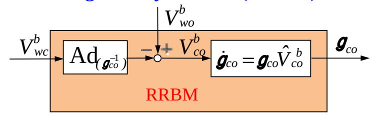
↓

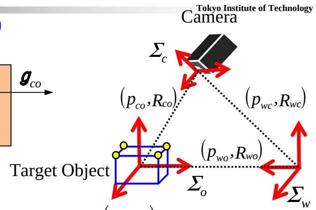
The estimation error (e_e) is equal to zero , then the estimated relative pose ($\bar{g}_{co}$) equals the real relative pose (g_{co})

VMO can estimate the relative pose (3D) from image information (2D)

Introduction

Relative Rigid Body Motion (RRBM)





Body Velocity of Object

$$V^b_{wo} = \begin{bmatrix} v^b_{wo} \\ \omega^b_{wo} \end{bmatrix} \quad \hat{V}^b_{wo} = g^{-1}_{wo}\dot{g}_{wo}$$

Body Velocity of Camera

$$V^b_{wc} = \begin{bmatrix} v^b_{wc} \\ \omega^b_{wc} \end{bmatrix} \quad \hat{V}^b_{wc} = g^{-1}_{wc}\dot{g}_{wc}$$

Body Velocity of Object relative to Camera

$$V^b_{co} = \begin{bmatrix} v^b_{co} \\ \omega^b_{co} \end{bmatrix} \quad \hat{V}^b_{co} = g^{-1}_{co}\dot{g}_{co}$$

RRBM

$$V^b_{co} = -\mathrm{Ad}_{(g^{-1}_{co})} V^b_{wc} + V^b_{wo}$$

$g = (p, R) \in SE(3)$

$p \in \Re^3$: Position

$R \in SO(3)$: Orientation

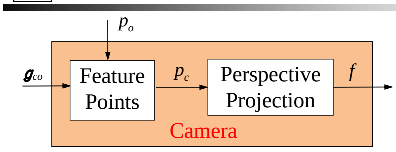
$v^b \in \Re^3$: Linear velocity

$\omega^b \in \Re^3$: Angular velocity

Adjoint Transformation

$$\mathrm{Ad}_{(g^{-1}_{co})} = \begin{bmatrix} R^T_{co} & -R^T_{co}\hat{p}_{co} \\ 0 & R^T_{co} \end{bmatrix} \in \Re^{6\times 6}$$

Introduction



i-th Feature Point

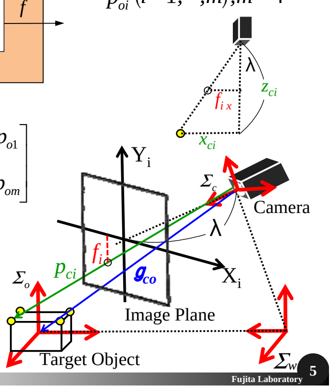
$p_{oi}\ (i = 1, \cdots, m), m = 4$

Relative *i*-th Feature Point

$$p_{ci} = g_{co} p_{oi} = \begin{bmatrix} x_{ci} \\ y_{ci} \\ z_{ci} \end{bmatrix} \quad p_c = \begin{bmatrix} p_{c1} \\ \vdots \\ p_{cm} \end{bmatrix} = \begin{bmatrix} g_{co} p_{o1} \\ \vdots \\ g_{co} p_{om} \end{bmatrix}$$

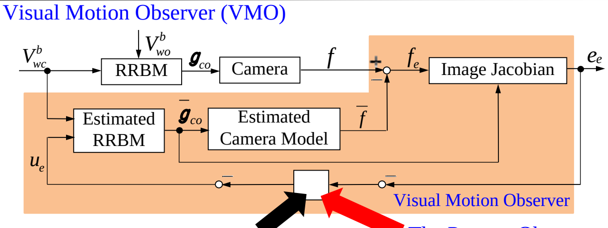
Perspective Projection

$$f_i = \begin{bmatrix} f_{xi} \\ f_{yi} \end{bmatrix} = \frac{\lambda}{z_{ci}} \begin{bmatrix} x_{ci} \\ y_{ci} \end{bmatrix} \quad f = \begin{bmatrix} f_1 \\ \vdots \\ f_m \end{bmatrix} = \begin{bmatrix} \frac{\lambda}{z_{c1}} x_{c1} \\ \frac{\lambda}{z_{c1}} y_{c1} \\ \vdots \\ \frac{\lambda}{z_{cm}} x_{cm} \\ \frac{\lambda}{z_{cm}} y_{cm} \end{bmatrix}$$



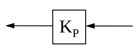
Introduction

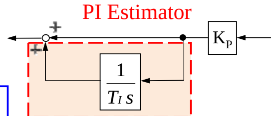
Visual Motion Observer (VMO)



The Conventional Observer
P Estimator

The Present Observer
PI Estimator





P estimator causes estimated error [1]

↓

PI estimator cancels estimated error [2]

K_p : Proportional gain

T_I : Integration time

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Simulation

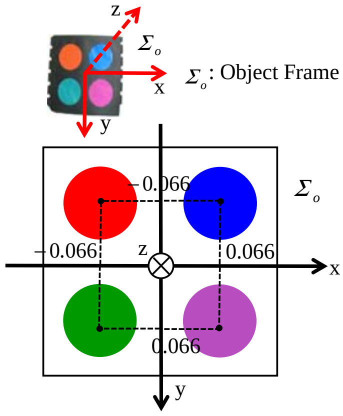
Feature Points

Red : $p_{o1} = \begin{bmatrix} -0.066 \\ -0.066 \\ 0 \end{bmatrix}$ [m]

Blue : $p_{o2} = \begin{bmatrix} 0.066 \\ -0.066 \\ 0 \end{bmatrix}$ [m]

Green : $p_{o3} = \begin{bmatrix} -0.066 \\ 0.066 \\ 0 \end{bmatrix}$ [m]

Purple : $p_{o4} = \begin{bmatrix} 0.066 \\ 0.066 \\ 0 \end{bmatrix}$ [m]



Simulation

Initial value

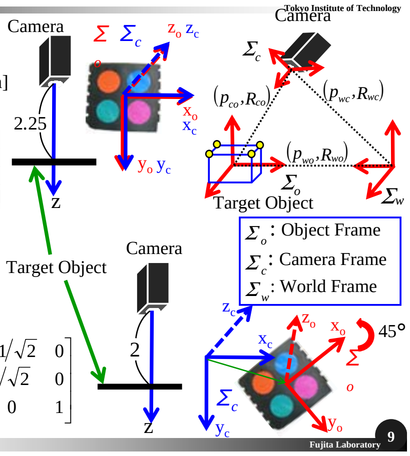
Position : $p_{co} = \begin{bmatrix} 0 \\ 0 \\ 2.25 \end{bmatrix}$ [m]

Orientation: $R_{co} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

Initial value of estimation

Position : $\bar{p}_{co} = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}$ [m]

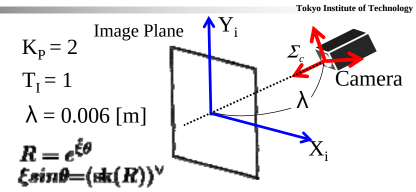
Orientation: $\bar{R}_{co} = \begin{bmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$



Simulation

Setting

Proportional Gain	$K_P = 2$
Integral Time	$T_I = 1$
Focal Length	$\lambda = 0.006$ [m]
Exponential Expression	$R = e^{\hat{\xi}\theta}$ $\xi\sin\theta = (sk(R))^\vee$



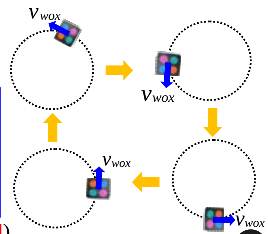
Input Signal

Body Velocity of Object : $V^b_{wo} = \begin{bmatrix} v^b_{wo} \\ \omega^b_{wo} \end{bmatrix}$

(Constant velocity)

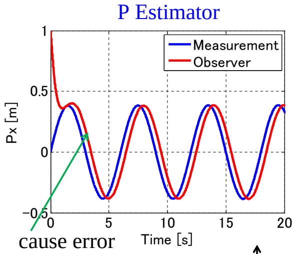
Linear velocity: $\begin{bmatrix} v^b_{wox} \\ v^b_{woy} \\ v^b_{woz} \end{bmatrix} = \begin{bmatrix} 0.4 \\ 0 \\ 0 \end{bmatrix}$ [m/s]

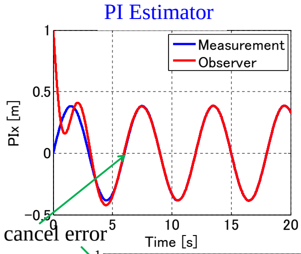
Angular velocity: $\begin{bmatrix} \omega^b_{wox} \\ \omega^b_{woy} \\ \omega^b_{woz} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \pi/3 \end{bmatrix}$ [rad/s]



Body Velocity of Camera : $V^b_{wc} = 0$ (Fixed)

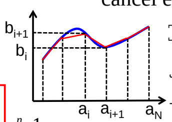
Position (X motion)





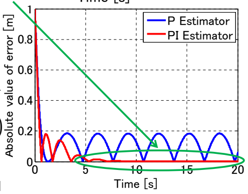
Error of Measurement and Observer

Numerical Integration	
P Estimator	2.5011
PI Estimator	0.6476

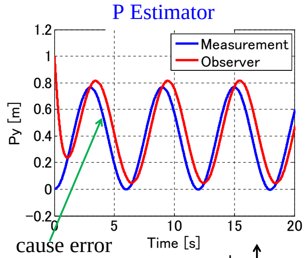


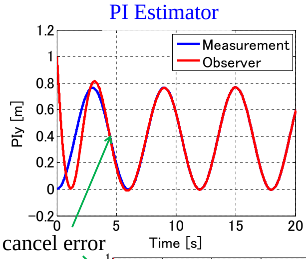
$$\sum_{i=0}^{n} \frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$$

Trapezoidal Rule



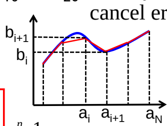
Position (Y motion)





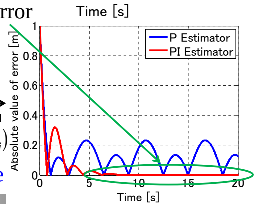
Error of Measurement and Observer

Numerical Integration	
P Estimator	2.6804
PI Estimator	0.8491



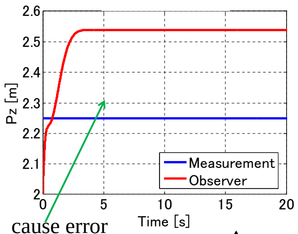
$$\sum_{i=0}^{n} \frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$$

Trapezoidal Rule

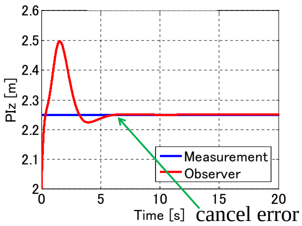


Position (Z motion)

P Estimator



PI Estimator

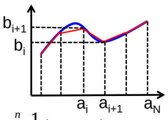


cause error

cancel error

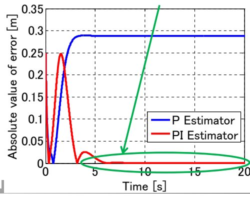
Error of Measurement and Observer

Numerical Integration	
P Estimator	5.3553
PI Estimator	0.4416



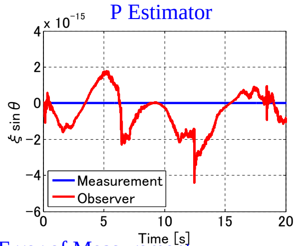
$$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$$

Trapezoidal Rule

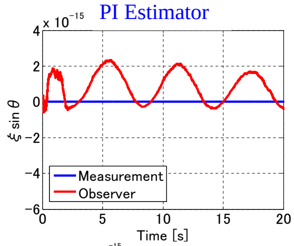


Orientation (X motion)

P Estimator



PI Estimator

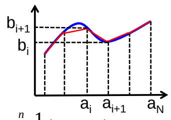


Error of Measurement and Observer

Numerical Integration

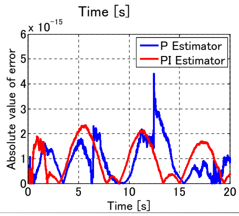
P Estimator 1.8169×10^{-14}

PI Estimator 1.9170×10^{-14}



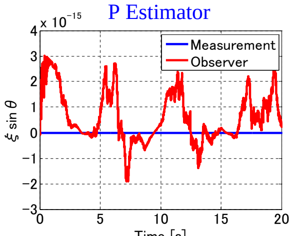
$$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$$

Trapezoidal Rule

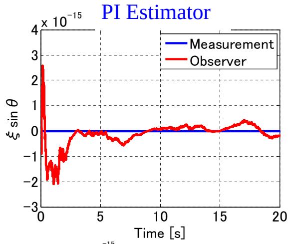


Orientation (Y motion)

P Estimator



PI Estimator

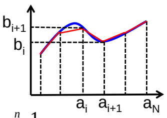


Error of Measurement and Observer

Numerical Integration

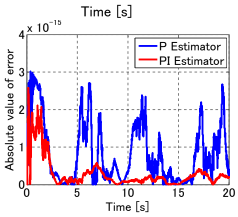
P Estimator 1.6918×10^{-14}

PI Estimator 5.8170×10^{-15}



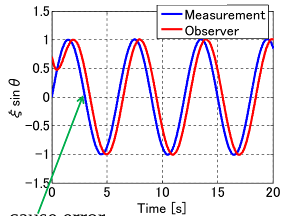
$$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$$

Trapezoidal Rule

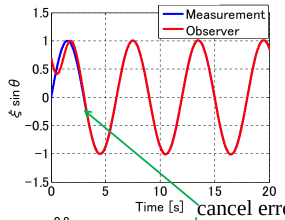


Orientation (Z motion)

P Estimator



PI Estimator

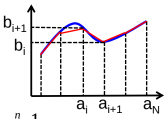


cause error

cancel error

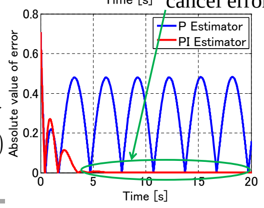
Error of Measurement and Observer

Numerical Integration	
P Estimator	5.8526
PI Estimator	0.4809



$$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$$

Trapezoidal Rule



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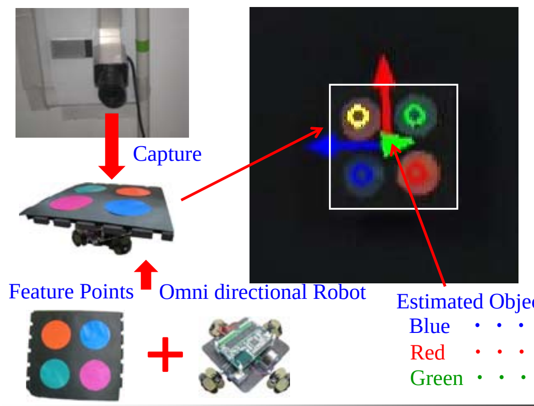
Experimental Environment

Camera

Field from Overhead Camera



Estimated Object Frame

Blue ・・・ X axis

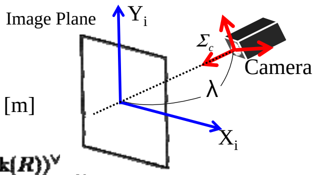
Red ・・・ Y axis

Green ・・・ Z axis

Experimental Environment

Setting

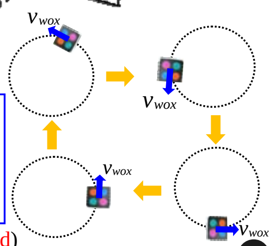
- Proportional Gain $K_P = 2$
- Integral Time $T_I = 1$
- Focal Length $\lambda=0.006$ [m]
- Exponential Expression $R = e^{\hat{\xi}\theta}$, $\xi \sin\theta = (\mathrm{sk}(R))^{\vee}$



Input Signal

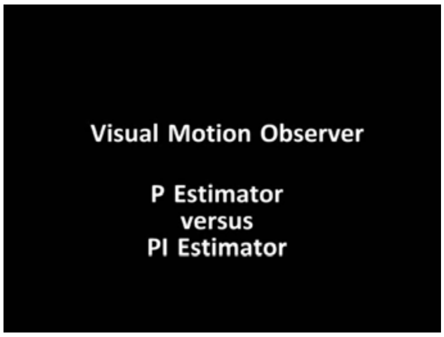
Body Velocity of Object : $V^b_{wo} = \begin{bmatrix} v^b_{wo} \\ \omega^b_{wo} \end{bmatrix}$
(Constant velocity)

Linear velocity	Angular velocity
$\begin{bmatrix} v^b_{wox} \\ v^b_{woy} \\ v^b_{woz} \end{bmatrix} = \begin{bmatrix} 0.4 \\ 0 \\ 0 \end{bmatrix}$ [m/s]	$\begin{bmatrix} \omega^b_{wox} \\ \omega^b_{woy} \\ \omega^b_{woz} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \pi/3 \end{bmatrix}$ [rad/s]



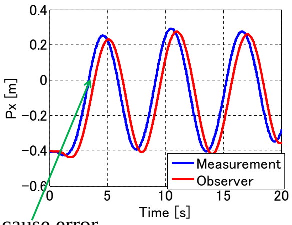
Body Velocity of Camera : $V^b_{wc} = 0$ (Fixed)

Movie



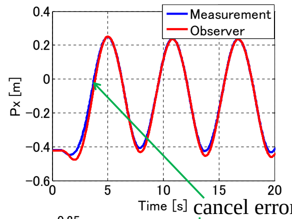
Position (X motion)

P Estimator



cause error

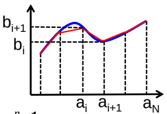
PI Estimator



cancel error

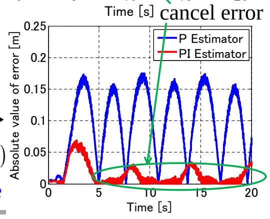
Error of Measurement and Observer

Numerical Integration	
P Estimator	1.8753
PI Estimator	0.2656



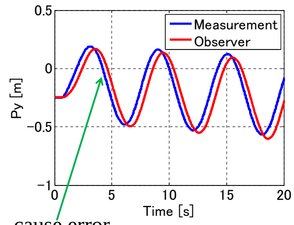
$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$

Trapezoidal Rule



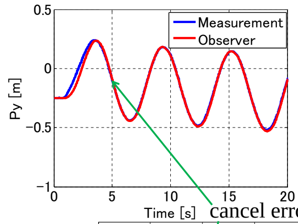
Position (Y motion)

P Estimator



cause error

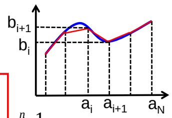
PI Estimator



cancel error

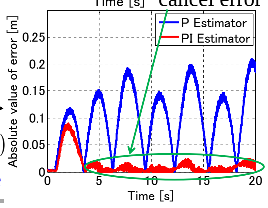
Error of Measurement and Observer

Numerical Integration	
P Estimator	1.9557
PI Estimator	0.2512



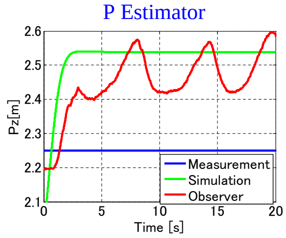
$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$

Trapezoidal Rule

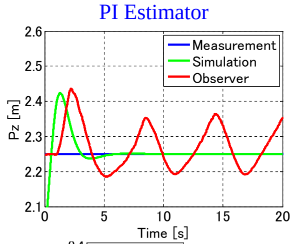


Position (Z motion)

P Estimator

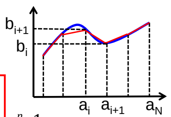


PI Estimator



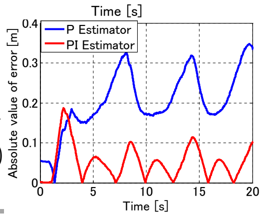
Error of Measurement and Observer

Numerical Integration	
P Estimator	4.0774
PI Estimator	1.0384



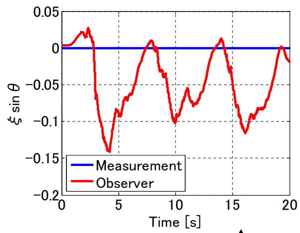
$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$

Trapezoidal Rule

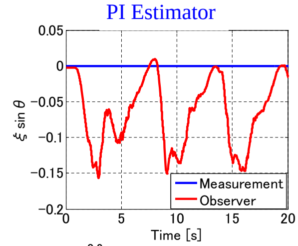


Orientation (X motion)

P Estimator

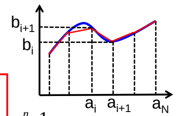


PI Estimator



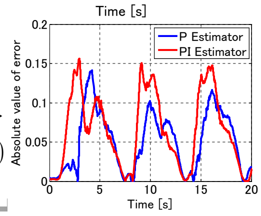
Error of Measurement and Observer

Numerical Integration	
P Estimator	1.0141
PI Estimator	1.2970



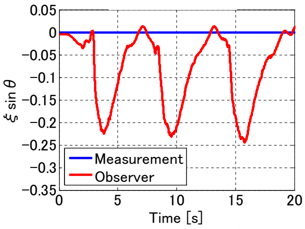
$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$

Trapezoidal Rule

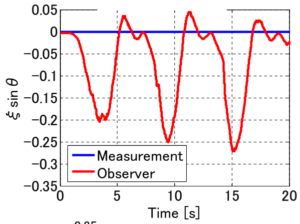


Orientation (Y motion)

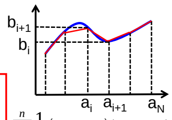
P Estimator



PI Estimator

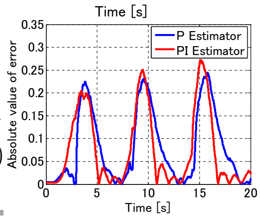


Error of Measurement and Observer



$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$

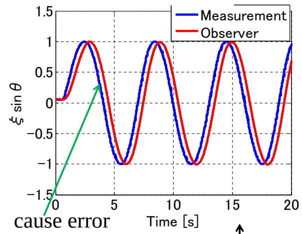
Trapezoidal Rule



Numerical Integration	
P Estimator	1.6325
PI Estimator	1.5297

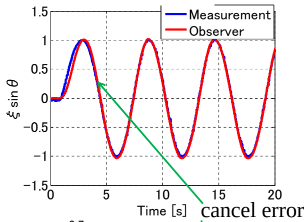
Orientation (Z motion)

P Estimator



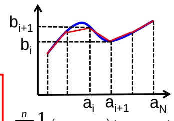
cause error

PI Estimator



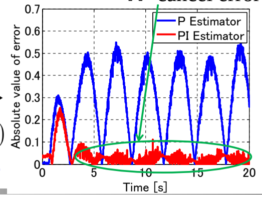
cancel error

Error of Measurement and Observer



$\sum_{i=0}^{n}\frac{1}{2}(b_{i+1}+b_i)(a_{i+1}-a_i)$

Trapezoidal Rule



Numerical Integration	
P Estimator	5.6779
PI Estimator	0.7022

Outline

- Introduction
- Simulation
  - Setting
  - Position
  - Orientation
- Experiment
  - Experimental Environment
  - Position
  - Orientation
- Conclusion and Future Works

Conclusion and Future Works

Simulation

- P Estimator causes estimated error for both position and orientation (Z motion)
- PI Estimator cancels estimated error for both position and orientation

Experiment

- P Estimator causes estimated error for both position and orientation
- PI Estimator cancels estimated error for both position (X motion and Y motion) and orientation (Z motion)
- The fluctuation in Z motion of position and in X motion and Y motion of orientation are caused by the measurement noise and lens distortion

Future Works

- Body Velocity of Object $V^b_{wo} = \text{const}$ ➡ $V^b_{wo} \neq \text{const}$
- Body Velocity of Camera $V^b_{wc} = 0$ ➡ $V^b_{wc} \neq 0$

Reference

[1] T. Hatanaka and M. Fujita, "Passivity-based Visual Motion Observer: From Theory to Distributed Algorithms," *Tutorial Session on Computer Vision and Control for the CACSD component on the IEEE 2010 MSC*, Tokyo, Japan, 8th, Sep., pp. 1210-1221, 2010.

[2] T. Hatanaka and M. Fujita "Passivity-based Visual Motion Observer Integrating Internal Representation of 3D Target Object Motion," *Proc. of the 2012 American Control Conference*, Montreal, Canada, 2012.

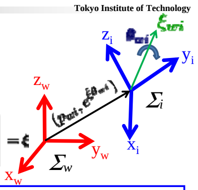
Appendix

Exponential Expression

$e^{\hat{\xi}\theta_{wi}} \in SO(3)$ $\xi_{wi} \in \Re^3$: Rotation Axis $(\|\xi_{wi}\| = 1)$
$\theta_{wi} \in \Re$: Rotation Angle $(|\theta_{wi}| < \pi)$

"$\wedge$" (wedge): $\Re^3 \rightarrow so(3)$ "$\vee$" (vee) : $so(3) \rightarrow \Re^3$

$$\hat{\xi} = \begin{bmatrix}\xi_x \\ \xi_y \\ \xi_z\end{bmatrix}^{\wedge} = \begin{bmatrix}0 & -\xi_z & \xi_y \\ \xi_z & 0 & -\xi_x \\ -\xi_y & \xi_x & 0\end{bmatrix} \quad \begin{bmatrix}0 & -\xi_z & \xi_y \\ \xi_z & 0 & -\xi_x \\ -\xi_y & \xi_x & 0\end{bmatrix}^{\vee} = \begin{bmatrix}\xi_x \\ \xi_y \\ \xi_z\end{bmatrix} = \xi$$



Skew-symmetric Component

$$\mathrm{sk}(e^{\hat{\xi}\theta_{wi}}) = \frac{1}{2}(e^{\hat{\xi}\theta_{wi}} - e^{-\hat{\xi}\theta_{wi}})$$
$$= \hat{\xi}\theta_{wi} + \frac{(\hat{\xi}\theta_{wi})^3}{3!} + \frac{(\hat{\xi}\theta_{wi})^5}{5!} + \cdots$$
$$= \hat{\xi}(\theta_{wi} - \frac{(\theta_{wi})^3}{3!} + \frac{(\theta_{wi})^5}{5!} - \cdots)$$
$$= \hat{\xi}\sin\theta_{wi}$$
$$(\mathrm{sk}(e^{\hat{\xi}\theta_{wi}}))^{\vee} = \xi\sin\theta_{wi}$$

Maclaurin expansion

$$e^{\hat{\xi}\theta_{wi}} = I + \hat{\xi}\theta_{wi} + \frac{(\hat{\xi}\theta_{wi})^2}{2!} + \cdots$$
$$e^{-\hat{\xi}\theta_{wi}} = I - \hat{\xi}\theta_{wi} + \frac{(-\hat{\xi}\theta_{wi})^2}{2!} + \cdots$$
$$\sin\theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \cdots$$

$$\hat{\xi}^3 = -\|\xi\|^2\hat{\xi} = -\hat{\xi} \qquad \hat{\xi}^5 = -\|\xi\|^2\hat{\xi}^3 = \|\xi\|^4\hat{\xi} = \hat{\xi} \qquad \vdots$$

Image Jacobian

f_e → Image Jacobian → e_e

Estimation error (e_e) can be computed using image information (f_e)

Image Jacobian

$$J = \begin{bmatrix}J_1 \\ \vdots \\ J_n\end{bmatrix}\begin{bmatrix}\bar{R} & 0 \\ 0 & \bar{R}\end{bmatrix} = \begin{bmatrix}\frac{\lambda}{\bar{z}_{c1}} & 0 & -\frac{\lambda\bar{x}_{c1}}{\bar{z}_{c1}^2} & 0 & & 0 \\ 0 & \frac{\lambda}{\bar{z}_{c1}} & -\frac{\lambda\bar{y}_{c1}}{\bar{z}_{c1}^2} & & & \\ & 0 & & \ddots & & 0 \\ & & & & \frac{\lambda}{\bar{z}_{cn}} & 0 & -\frac{\lambda\bar{x}_{cn}}{\bar{z}_{cn}^2} \\ & 0 & & 0 & 0 & \frac{\lambda}{\bar{z}_{cn}} & -\frac{\lambda\bar{y}_{cn}}{\bar{z}_{cn}^2}\end{bmatrix}\begin{bmatrix}I & -(\hat{R}p_{c1})^{\vee} \\ \vdots & \vdots \\ I & -(\hat{R}p_{cn})^{\vee}\end{bmatrix}\begin{bmatrix}\bar{R} & 0 \\ 0 & \bar{R}\end{bmatrix}$$

$$f_e = f - \bar{f} = \begin{bmatrix}f_1 - \bar{f}_1 \\ \vdots \\ f_n - \bar{f}_n\end{bmatrix} = J\begin{bmatrix}p_{ee} \\ \mathrm{sk}(e^{\hat{\xi}\theta_{ee}})^{\vee}\end{bmatrix}$$

Estimation error : $e_e = \begin{bmatrix}p_{ee} \\ \mathrm{sk}(e^{\hat{\xi}\theta_{ee}})^{\vee}\end{bmatrix}$

$$J^{\dagger}f_e = (J^TJ)^{-1}J^Tf_e$$
$$= (J^TJ)^{-1}J^TJ\begin{bmatrix}p_{ee} \\ \mathrm{sk}(e^{\hat{\xi}\theta_{ee}})^{\vee}\end{bmatrix}$$
$$= e_e$$

Pseudo-inverse matrix : $J^{\dagger}$