Immersion and Invariance

[1] describe immersion and invariance as a new tool for stabilization and adaptive control of nonlinear systems. This work note have applied some the tools to a surface vessel which is affected by a external disturbance and uncertainties in the damping matrix and on the control input.

System

The 3 DOF dynamics of a surface vessel can be stated as:

$$\dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{\nu} \tag{1}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau} + \mathbf{R}^\top(\psi)\boldsymbol{w}, \tag{2}$$

where

$$\mathbf{R}(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

is a rotation matrix $\mathbf{R} \in SO(3)$, and where $\mathbf{M}$, $\boldsymbol{C}(\boldsymbol{\nu})$, $\boldsymbol{D}(\boldsymbol{\nu})$, $\boldsymbol{\tau}$ and $\boldsymbol{w}$ represent the real inertia matrix, Coriolis and centripetal matrix, damping matrix, control input vector and disturbance vector, respectively. Here, the system matrices are assumed to satisfy the properties $\mathbf{M} = \mathbf{M}^\top > 0$, $\mathbf{C}(\boldsymbol{\nu}) = -\mathbf{C}(\boldsymbol{\nu})^\top$ and $\mathbf{D}(\boldsymbol{\nu}) > 0$.

I & I adaptive control with only uncertainties in the damping matrix

We consider the dynamic ship model (1) and (2) which can be rewritten as

$$\dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{\nu} \tag{4}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} = \boldsymbol{\tau} - \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{g}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{\Phi}(\boldsymbol{\nu})\boldsymbol{\varphi}. \tag{5}$$

Here, $\boldsymbol{g}(\boldsymbol{\nu})\boldsymbol{\nu}$ is the know part of $-\boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu}$ and

$$\boldsymbol{\varphi} = \left[Y_{|r|v}, Y_r, Y_{|v|r}, Y_{|r|r}, N_{|r|v}, N_r, N_{|v|r}, N_{|r|r}\right]^\top \tag{6}$$

$$\boldsymbol{\Phi}(\boldsymbol{\nu}) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ |r|v & r & |v|r & |r|r & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & |r|v & r & |v|r & |r|r \end{bmatrix} \tag{7}$$

Start by defining the error variables $\mathbf{z}_1$ and $\mathbf{z}_2$:

$$\mathbf{z}_1 \triangleq \mathbf{R}^\top(\psi)(\boldsymbol{\eta} - \boldsymbol{\eta}_d) \tag{8}$$

$$\mathbf{z}_2 \triangleq \boldsymbol{\nu} - \boldsymbol{\alpha}, \tag{9}$$

where $\boldsymbol{\alpha} \in \mathbb{R}^3$ is a vector of stabilising functions to be designed.

The stabilising function can now be chosen as

$$\boldsymbol{\alpha} = \mathbf{R}^\top(\psi)\dot{\boldsymbol{\eta}}_d - \mathbf{K}_1\mathbf{z}_1, \tag{10}$$

where $\mathbf{K}_1 > 0$.

Let the estimation error $\boldsymbol{s}$ be defined as

$$\boldsymbol{s} = \hat{\boldsymbol{\varphi}} - \boldsymbol{\varphi} + \boldsymbol{\beta}(\mathbf{z}) \tag{11}$$

After differentiating (11) with respect to time, the dynamics of $\boldsymbol{s}$ is given by

$$\begin{aligned} \dot{\boldsymbol{s}} &= \dot{\hat{\boldsymbol{\varphi}}} + \frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_1^\top}\dot{\mathbf{z}}_1 + \frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_2^\top}\dot{\mathbf{z}}_2 & (12)\\ &= \dot{\hat{\boldsymbol{\varphi}}} + \frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_1^\top}\dot{\mathbf{z}}_1 + \frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_2^\top}\left(\boldsymbol{\tau} - \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{g}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{\Phi}(\boldsymbol{\nu})(\hat{\boldsymbol{\varphi}} + \boldsymbol{\beta}(\mathbf{z}) - \boldsymbol{s}) - \boldsymbol{M}\dot{\boldsymbol{\alpha}}\right) & (13) \end{aligned}$$

Based on [2], the adaptive state feedback update law $\hat{\boldsymbol{\varphi}}$ and control input $\boldsymbol{\tau}$ are designed as follows:

$$\begin{aligned} \dot{\hat{\boldsymbol{\varphi}}} &= -\frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_1^\top}\dot{\mathbf{z}}_1 - \frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_2^\top}\left(\boldsymbol{\tau} - \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{g}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{\Phi}(\boldsymbol{\nu})(\hat{\boldsymbol{\varphi}} + \boldsymbol{\beta}(\mathbf{z})) - \boldsymbol{M}\dot{\boldsymbol{\alpha}}\right) & (14)\\ \boldsymbol{\tau} &= -\mathbf{K}_2\mathbf{z}_2 - \mathbf{z}_1 + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} - \boldsymbol{g}(\boldsymbol{\nu})\boldsymbol{\nu} - \boldsymbol{\Phi}(\boldsymbol{\nu})(\hat{\boldsymbol{\varphi}} + \boldsymbol{\beta}(\mathbf{z})) + \boldsymbol{M}\dot{\boldsymbol{\alpha}} & (15) \end{aligned}$$

Based on [3] we select

$$\begin{aligned} \frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_1^\top} &= 0 & (16)\\ \frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_2^\top} &= \Gamma\boldsymbol{\Phi}(\boldsymbol{\nu})^\top & (17) \end{aligned}$$

According to this the adaptive state feedback update law $\hat{\boldsymbol{\varphi}}$ and control input $\boldsymbol{\tau}$ for the system are

$$\begin{aligned} \dot{\hat{\boldsymbol{\varphi}}} &= -\boldsymbol{\Gamma}\boldsymbol{\Phi}(\boldsymbol{\nu})^\top\left(\boldsymbol{\tau} - \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{g}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{\Phi}(\boldsymbol{\nu})(\hat{\boldsymbol{\varphi}} + \boldsymbol{\Gamma}\boldsymbol{\Phi}(\boldsymbol{\nu})^\top\mathbf{z}_2) - \boldsymbol{M}\dot{\boldsymbol{\alpha}}\right) & (18)\\ \boldsymbol{\tau} &= -\mathbf{K}_2\mathbf{z}_2 - \mathbf{z}_1 + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} - \boldsymbol{g}(\boldsymbol{\nu})\boldsymbol{\nu} - \boldsymbol{\Phi}(\boldsymbol{\nu})(\hat{\boldsymbol{\varphi}} + \boldsymbol{\Gamma}\boldsymbol{\Phi}(\boldsymbol{\nu})^\top\mathbf{z}_2) + \boldsymbol{M}\dot{\boldsymbol{\alpha}}. & (19) \end{aligned}$$

Substituting (19) into (18) and (13), they become

$$\begin{aligned} \dot{\hat{\boldsymbol{\varphi}}} &= -\boldsymbol{\Gamma}\boldsymbol{\Phi}(\boldsymbol{\nu})^\top(-\mathbf{K}_2\mathbf{z}_2 - \mathbf{z}_1) & (20)\\ \dot{\boldsymbol{s}} &= \dot{\hat{\boldsymbol{\varphi}}} + \boldsymbol{\Gamma}\boldsymbol{\Phi}(\boldsymbol{\nu})^\top(-\mathbf{K}_2\mathbf{z}_2 - \mathbf{z}_1 - \boldsymbol{\Phi}(\boldsymbol{\nu})\boldsymbol{s}) & \\ &= -\boldsymbol{\Gamma}\boldsymbol{\Phi}(\boldsymbol{\nu})^\top\boldsymbol{\Phi}(\boldsymbol{\nu})\boldsymbol{s} & (21) \end{aligned}$$

Choosing a positive definite control Lyapunov functions (CLF)

$$V_1 = \frac{1}{2}\mathbf{z}_1^\top\mathbf{z}_1 + \frac{1}{2}\mathbf{z}_2^\top\boldsymbol{M}\mathbf{z}_2 + \frac{1}{2}\boldsymbol{s}^\top\boldsymbol{s} \tag{22}$$

the derivative of V_1 with respect to (w.r.t) time along the dynamics gives

$$\begin{aligned} \dot{V}_1 &= \mathbf{z}_1^\top\dot{\mathbf{z}}_1 + \mathbf{z}_2^\top\boldsymbol{M}\dot{\mathbf{z}}_2 + \boldsymbol{s}^\top\dot{\boldsymbol{s}} & \\ &= -\mathbf{z}_1^\top\mathbf{K}_1\mathbf{z}_1 - \mathbf{z}_2^\top(\mathbf{K}_2\mathbf{z}_2 + \boldsymbol{\Phi}(\boldsymbol{\nu})\boldsymbol{s}) - \boldsymbol{s}^\top\boldsymbol{\Gamma}\boldsymbol{\Phi}(\boldsymbol{\nu})^\top\boldsymbol{\Phi}(\boldsymbol{\nu})\boldsymbol{s} & (23)\\ \dot{V}_1 &\leq -\mathbf{z}_1^\top\mathbf{K}_1\mathbf{z}_1 - \frac{1}{2}\mathbf{z}_2^\top\mathbf{K}_2\mathbf{z}_2 - \frac{1}{2}1\boldsymbol{s}^\top\boldsymbol{\Gamma}\boldsymbol{\Phi}(\boldsymbol{\nu})^\top\boldsymbol{\Phi}(\boldsymbol{\nu})\boldsymbol{s} < 0 \quad \forall\mathbf{z}_1 \wedge \mathbf{z}_2 \wedge \boldsymbol{s} \neq 0. & (24) \end{aligned}$$

Comparing the I & I stability result with the stability result of an adaptive backstepping controller [4] which is

$$V_2 = \frac{1}{2}\mathbf{z}_1^\top \mathbf{z}_1 + \frac{1}{2}\mathbf{z}_2^\top \boldsymbol{M}\mathbf{z}_2 + \frac{1}{2}\tilde{\boldsymbol{\varphi}}^\top \tilde{\boldsymbol{\varphi}}. \tag{25}$$

And the derivative of V_2 with respect to (w.r.t) time along the dynamics gives

$$\begin{aligned}
\dot{V}_2 &= \mathbf{z}_1^\top \dot{\mathbf{z}}_1 + \mathbf{z}_2^\top \boldsymbol{M}\dot{\mathbf{z}}_2 + \tilde{\boldsymbol{\varphi}}^\top \dot{\tilde{\boldsymbol{\varphi}}} \\
&= -\mathbf{z}_1^\top \mathbf{K}_1 \mathbf{z}_1 - \mathbf{z}_2^\top (\mathbf{K}_2\mathbf{z}_2 + \boldsymbol{\Phi}(\boldsymbol{\nu})\tilde{\boldsymbol{\varphi}}) + \tilde{\boldsymbol{\varphi}}^\top \boldsymbol{\Gamma}\boldsymbol{\Phi}(\boldsymbol{\nu})^\top \mathbf{z}_2 && (26) \\
&= -\mathbf{z}_1^\top \mathbf{K}_1 \mathbf{z}_1 - \mathbf{z}_2^\top \mathbf{K}_2 \mathbf{z}_2. && (27)
\end{aligned}$$

Consult [5] for more details about the control algorithm and stability analysis.

Comparing Performance between I & I and AB

The control and adaptation gain are chosen as $\mathbf{K}_1 = diag([0.05, 0.05, 0.22])$, $\mathbf{K}_2 = diag([5, 7, 15])$ and $\boldsymbol{\Gamma} = diag([8, 4, 8, 8, 8, 4, 8, 8])$.

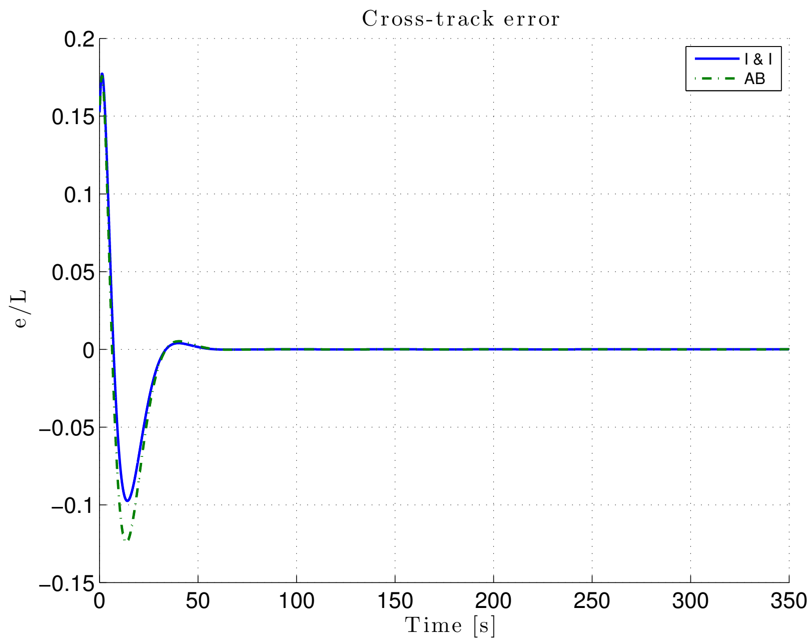

Figure 1: The cross-track error scaled by the vessel length, in the straight-line motion scenario

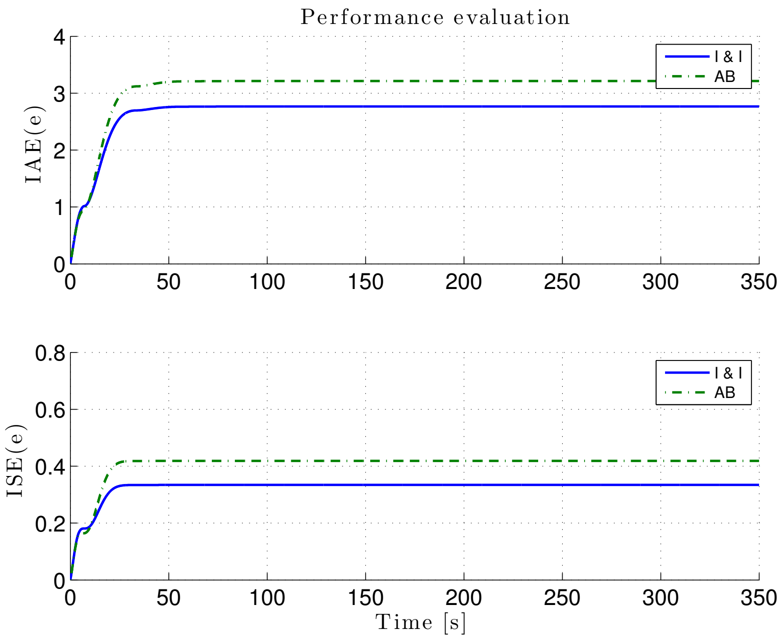

Figure 2: The IAE and ISE of the cross-track error in the straight-line motion scenario

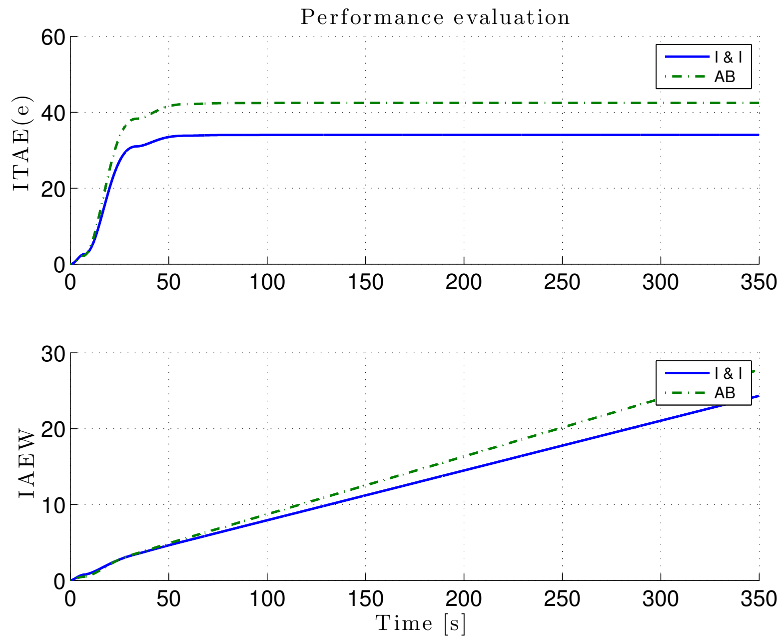

Figure 3: The ITAE and IAEW of the cross-track error in the straight-line motion scenario

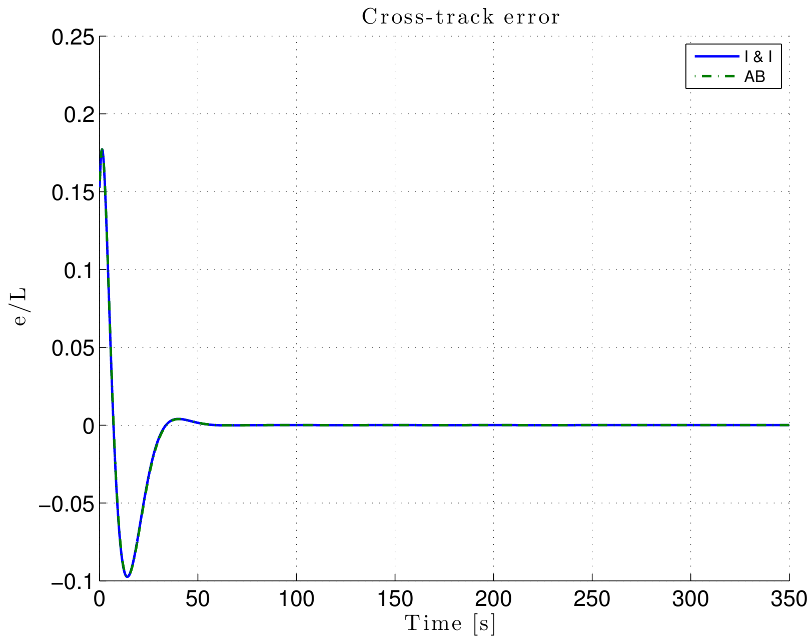

Figure 4: The cross-track error scaled by the vessel length, in the straight-line motion scenario

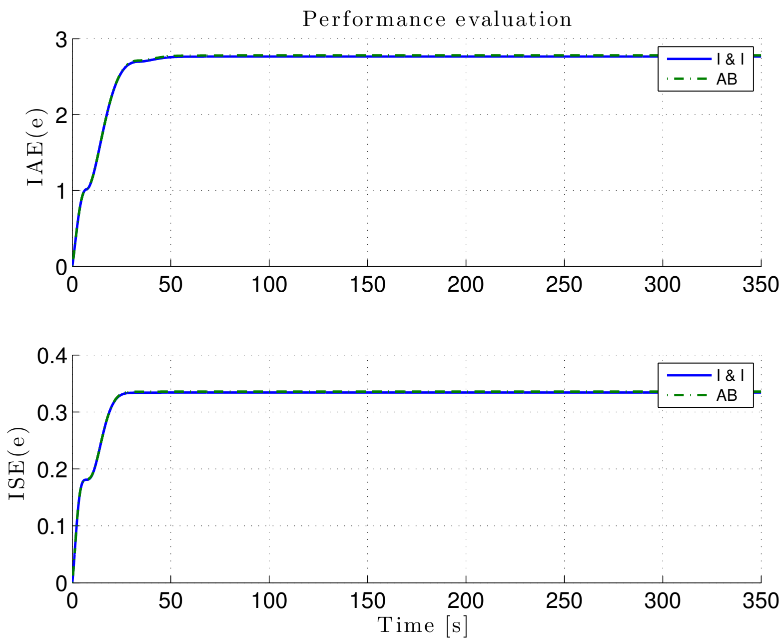

Figure 5: The IAE and ISE of the cross-track error in the straight-line motion scenario

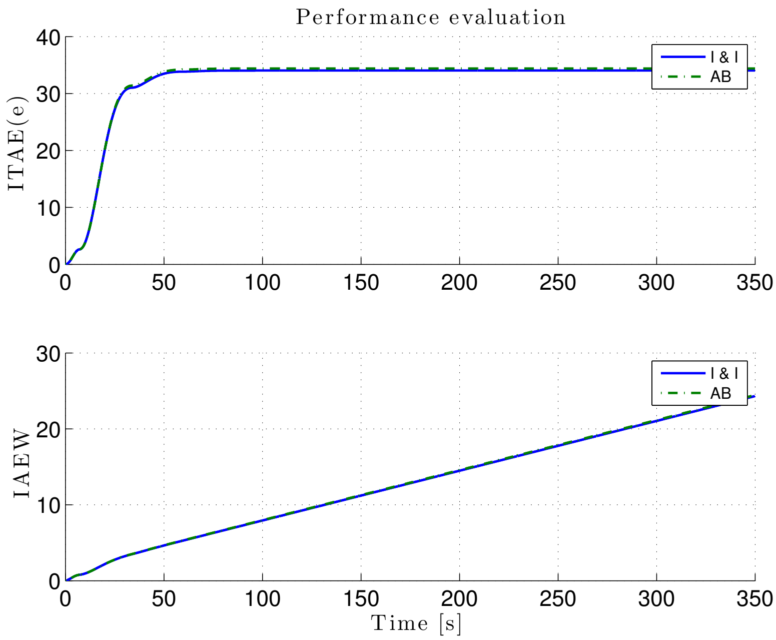

Figure 6: The ITAE and IAEW of the cross-track error in the straight-line motion scenario

Comparing Performance between I & I and AB with disturbance

$$\boldsymbol{\varphi} = \left[Y_{|r|v}, Y_r, Y_{|v|r}, Y_{|r|r}, N_{|r|v}, N_r, N_{|v|r}, N_{|r|r}, w_x^*, w_y^*, w_\psi^*\right]^\top \tag{28}$$

$$\boldsymbol{\Phi}(\boldsymbol{\nu}, \boldsymbol{\eta}) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cos(\psi) & \sin(\psi) & 0 \\ |r|v & r & |v|r & |r|r & 0 & 0 & 0 & 0 & -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 0 & 0 & |r|v & r & |v|r & |r|r & 0 & 0 & 1 \end{bmatrix} \tag{29}$$

The control and adaptation gain are chosen as $\mathbf{K}_1 = diag([0.05, 0.05, 0.22])$, $\mathbf{K}_2 = diag([5, 7, 15])$ and $\boldsymbol{\Gamma} = diag([8, 4, 8, 8, 8, 4, 8, 8, 0.4, 0.4, 0.4])$.

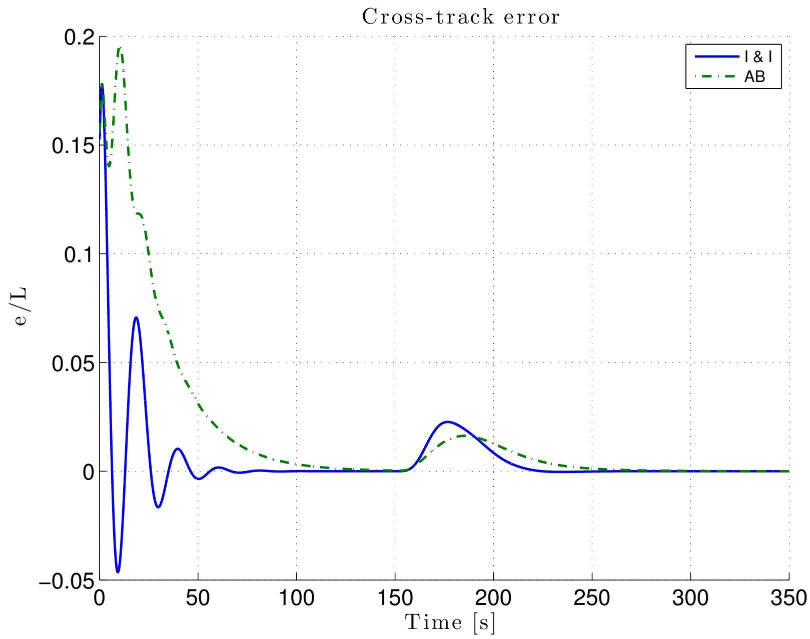

Figure 7: The cross-track error scaled by the vessel length, in the straight-line motion scenario

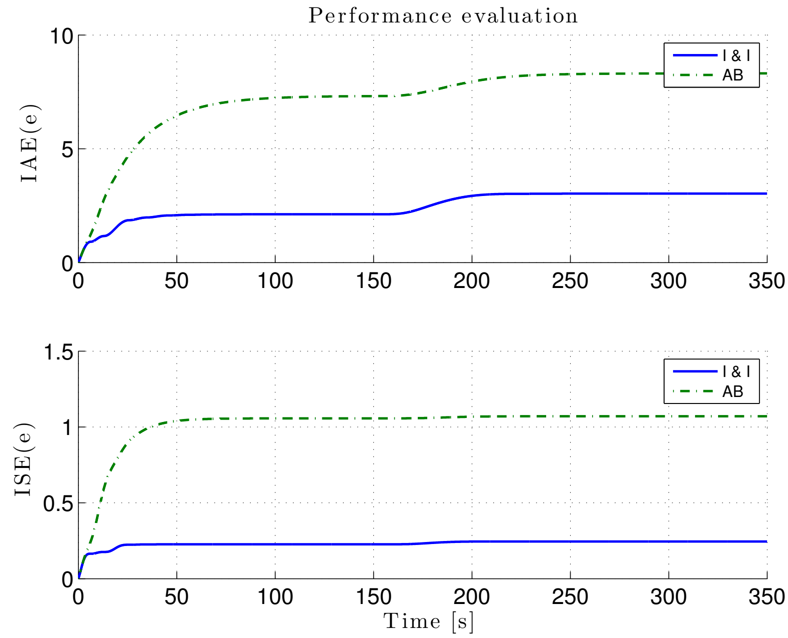

Figure 8: The IAE and ISE of the cross-track error in the straight-line motion scenario

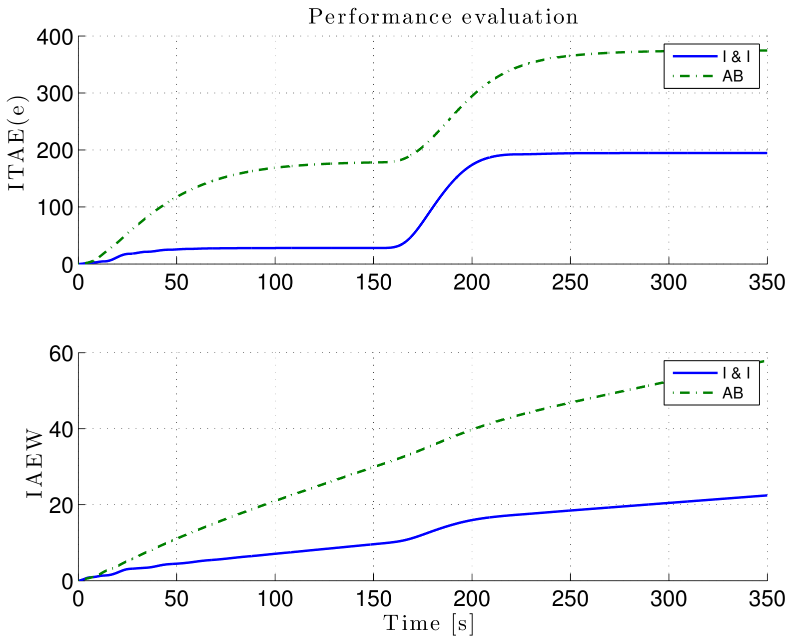

Figure 9: The ITAE and IAEW of the cross-track error in the straight-line motion scenario

Unknown Control Gain

Now, we consider the system

$$\dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{\nu} \tag{30}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} = \theta\boldsymbol{\tau} - \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{g}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{\Phi}(\boldsymbol{\nu}, \boldsymbol{\eta})\boldsymbol{\varphi}. \tag{31}$$

where $\theta \in \mathbb{R}$ and suppose that the sign of *theta* is known. Without loss of generality suppose that $\theta > 0$. The adaptation law and control from [5] and [6] are given as

$$\dot{\hat{\boldsymbol{\theta}}} = \left(\mathbf{I} + \frac{\partial \beta}{\partial \hat{\boldsymbol{\theta}}}\right)^{-1} \left(\frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_1}\dot{\mathbf{z}}_1 + \frac{\partial \boldsymbol{\beta}}{\partial \mathbf{z}_2}\dot{\mathbf{z}}_2\right)$$
$$\boldsymbol{\tau} = -\left(\hat{\theta} + \beta_2(\mathbf{z}, \hat{\boldsymbol{\varphi}})\right)(\mathbf{K}_2\mathbf{z}_2 + \mathbf{z}_1 - \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{g}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{\Phi}(\boldsymbol{\nu}, \boldsymbol{\eta})(\hat{\boldsymbol{\varphi}} + \boldsymbol{\beta}_1(\mathbf{z})) - \boldsymbol{M}\dot{\boldsymbol{\alpha}})$$

where $\hat{\boldsymbol{\theta}} = [\hat{\boldsymbol{\varphi}}^\top, \hat{\theta}]^\top$ and $\boldsymbol{\beta}(\cdot) = [\boldsymbol{\beta}_1(\cdot)^\top, \beta_2(\cdot)]^\top$, with

$$\boldsymbol{\beta}_1(\mathbf{z}) = \boldsymbol{\Gamma}_1 \int_0^{\mathbf{z}_2} \boldsymbol{\Phi}(\mathbf{z}_1, \boldsymbol{\xi}) d\boldsymbol{\xi} \tag{32}$$

$$\beta_2(\mathbf{z}, \hat{\boldsymbol{\varphi}}) = \gamma_2 \left(\frac{1}{2}\mathbf{z}_2^\top \mathbf{K}_2 \mathbf{z}_2 + \mathbf{z}_1^\top \mathbf{z}_2\right) + \gamma_2 \int_0^{\mathbf{z}_2} \boldsymbol{\Phi}(\mathbf{z}_1, \boldsymbol{\xi})^\top (\hat{\boldsymbol{\varphi}} + \boldsymbol{\beta}_1(\mathbf{z}_1, \boldsymbol{\xi})) d\boldsymbol{\xi}, \tag{33}$$

where $\mathbf{K}_2 > 0$, $\boldsymbol{\Gamma}_1 > 0$ and $\gamma_2 > 0$ and constant. Selecting

$$\boldsymbol{\beta}_1(\mathbf{z}) = \boldsymbol{\Gamma}_1 \boldsymbol{\Phi}(\boldsymbol{\nu})^\top \mathbf{z}_2 \tag{34}$$

$\beta_2(\mathbf{z}, \hat{\boldsymbol{\varphi}})$ becomes

$$\beta_2(\mathbf{z}, \hat{\boldsymbol{\varphi}}) = \gamma_2 \left(\frac{1}{2}\mathbf{z}_2^\top \mathbf{K}_2 \mathbf{z}_2 + \mathbf{z}_1^\top \mathbf{z}_2 + \hat{\boldsymbol{\varphi}}^\top \boldsymbol{\Phi}(\boldsymbol{\nu}, \boldsymbol{\eta})^\top \mathbf{z}_2 + \frac{1}{2}\mathbf{z}_2^\top \boldsymbol{\Phi}(\boldsymbol{\nu}, \boldsymbol{\eta})^\top \boldsymbol{\Gamma}_1 \boldsymbol{\Phi}(\boldsymbol{\nu}) \mathbf{z}_2\right) \tag{35}$$

From this the adaptation law become

$$\dot{\hat{\boldsymbol{\theta}}} = \left(\mathbf{I} + \begin{bmatrix} \mathbf{0}_{11\times 11} & \mathbf{0}_{11\times 1} \\ \mathbf{z}_2^\top \boldsymbol{\Phi}(\boldsymbol{\nu}, \boldsymbol{\eta}) & 0 \end{bmatrix}\right)^{-1} \begin{bmatrix} \boldsymbol{\Gamma}_1 \boldsymbol{\Phi}(\boldsymbol{\nu})^\top (-\mathbf{K}_2 \mathbf{z}_2 - \mathbf{z}_1) \\ \gamma_2 \left(\Delta(\cdot)\right) \end{bmatrix}, \tag{36}$$

where

$$\Delta(\cdot) = \mathbf{z}_2^\top \dot{\mathbf{z}}_1 + \mathbf{z}_2^\top \mathbf{K}_2 \dot{\mathbf{z}}_2 + \mathbf{z}_1^\top \dot{\mathbf{z}}_2 + \hat{\boldsymbol{\varphi}}^\top \boldsymbol{\Phi}(\boldsymbol{\nu}, \boldsymbol{\eta})^\top \dot{\mathbf{z}}_2 + \mathbf{z}_2^\top \boldsymbol{\Phi}(\boldsymbol{\nu}, \boldsymbol{\eta})^\top \boldsymbol{\Gamma}_1 \boldsymbol{\Phi}(\boldsymbol{\nu}) \dot{\mathbf{z}}_2 \tag{37}$$

Comparing Performance between I & I and AB with disturbance and Unknown Control Gain

$$\boldsymbol{\varphi} = \left[Y_{|r|v}, Y_r, Y_{|v|r}, Y_{|r|r}, N_{|r|v}, N_r, N_{|v|r}, N_{|r|r}, w_x^*, w_y^*, w_\psi^*\right]^\top \tag{38}$$

$$\boldsymbol{\Phi}(\boldsymbol{\nu}, \boldsymbol{\eta}) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cos(\psi) & \sin(\psi) & 0 \\ |r|v & r & |v|r & |r|r & 0 & 0 & 0 & 0 & -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 0 & 0 & |r|v & r & |v|r & |r|r & 0 & 0 & 1 \end{bmatrix} \tag{39}$$

The control and adaptation gain are chosen as $\mathbf{K}_1 = diag([0.05, 0.05, 0.22])$, $\mathbf{K}_2 = diag([5, 7, 15])$, $\boldsymbol{\Gamma}_1 = diag([8, 4, 8, 8, 8, 4, 8, 8, 0.4, 0.4, 0.4])$, $\theta = 0.4$ and $\gamma_2 = 2$.

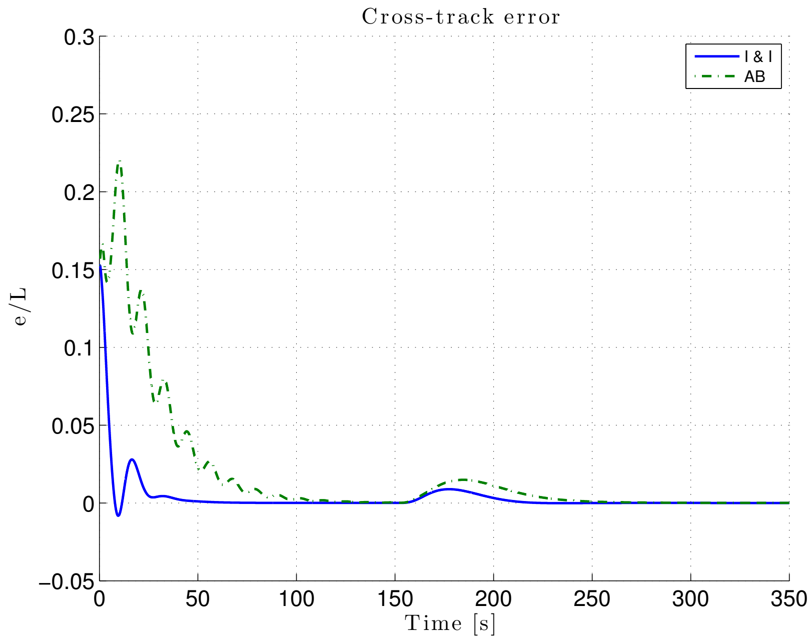

Figure 10: The cross-track error scaled by the vessel length, in the straight-line motion scenario

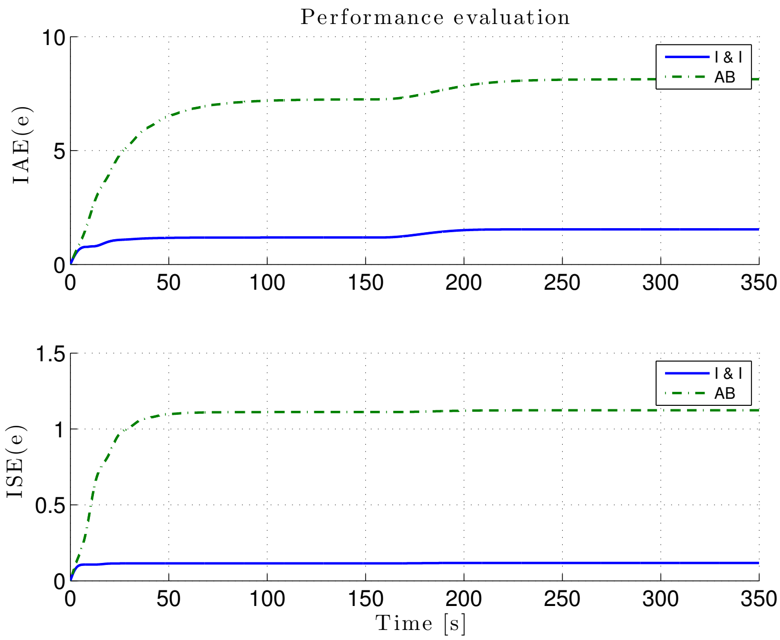

Figure 11: The IAE and ISE of the cross-track error in the straight-line motion scenario

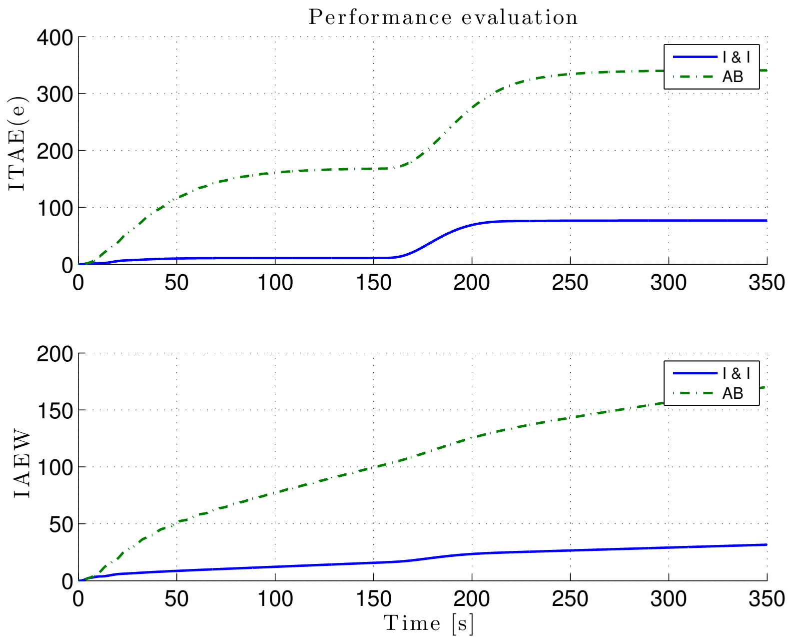

Figure 12: The ITAE and IAEW of the cross-track error in the straight-line motion scenario

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[2] B. Zhao, B. Xian, Y. Zhang, and X. Zhang, "Nonlinear robust adaptive tracking control of a quadrotor uav via immersion and invariance methodology," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 5, pp. 2891–2902, 2015.

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[6] D. Karagiannis and A. Astolfi, "Adaptive state feedback design via immersion and invariance," *In Proceeding of the 9th European Control Conference, Kos, Greece*, 2007.