Control Systems

Non Linear DP Controller

DYNAMIC POSITIONING CONFERENCE

September 17-18, 2002

Presented by

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Kawasaki Heavy Industries, Ltd.

DEVELOPMENT OF SHIP MANEUVERING CONTROL SYSTEM WITH ONLINE NONLINEAR OPTIMAL CONTROL

INTRODUCTION

- MOTIVATION
- REVIEW OF THE OPTIMAL CONTROL PROBLEM

OPTIMAL THRUST ALLOCATION

- FORMULATION
- EXPERIMENTAL RESULTS

ROUTE TRACKING

- FORMULATION
- EXPERIMENTAL RESULTS

CONCLUSION

Motivation

Requirements for Ship Maneuvering Control System

- Online Optimization for Nonlinear Model
- Minimize Fuel Consumption
- Minimize Environmental Effects (Wind, Current, Waves, …)
- Auto-rectification to Thruster Failure

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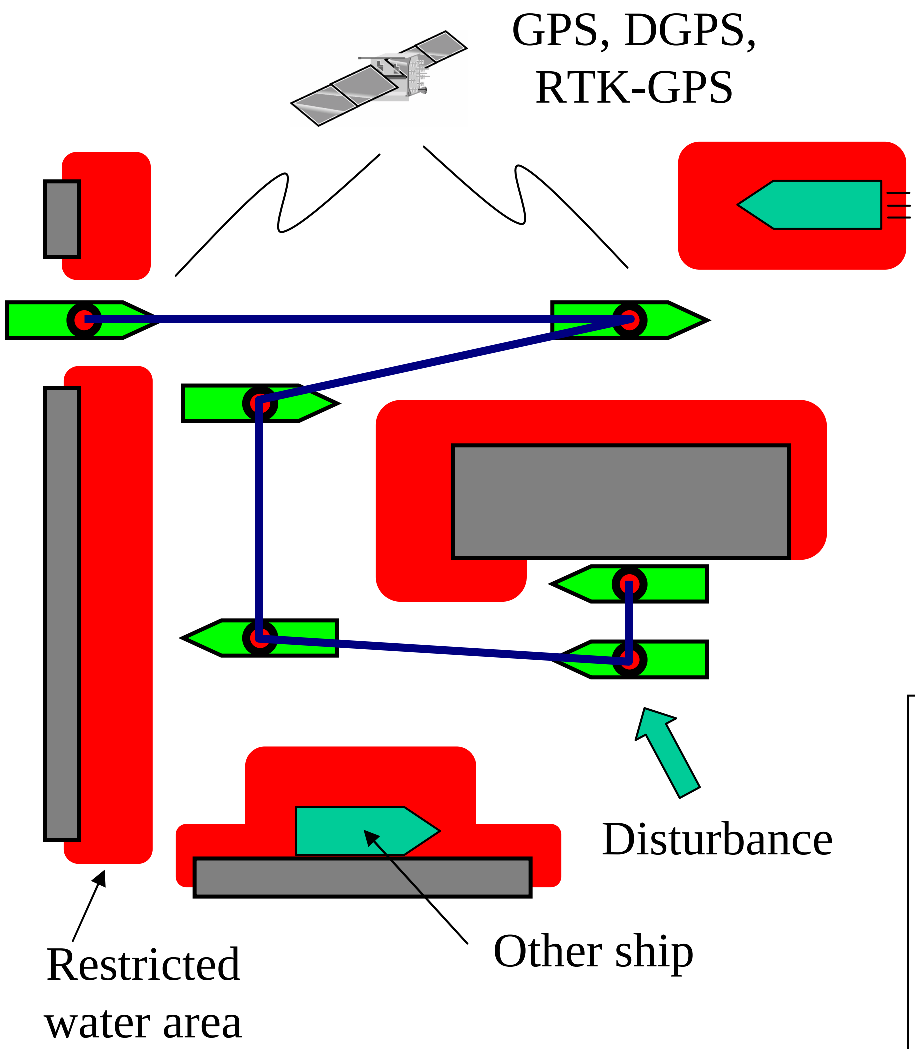
Motivation



Automatic berthing system in harbor

CONVENTIONAL STUDY

Offline calculation of tracking route by trial and error

Ship is controlled to track the pre-calculated route

Impractical !

Cannot deal with real disturbances, changing restricted conditions

OUR STUDY

Consideration of changing disturbance and restricted conditions by the Online Optimization

Realizable berthing assistant system

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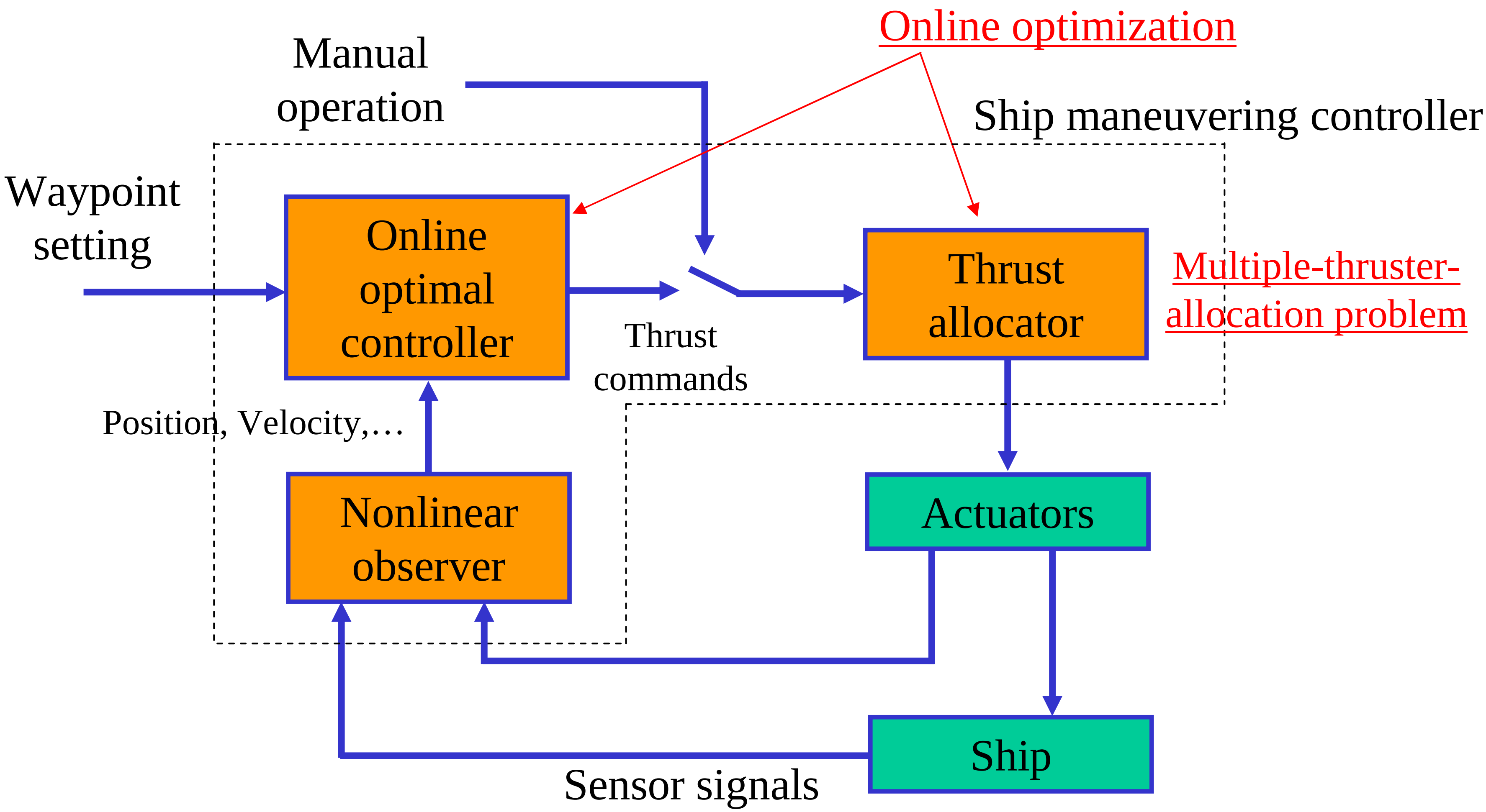
Basic Structure of Ship Maneuvering Controller



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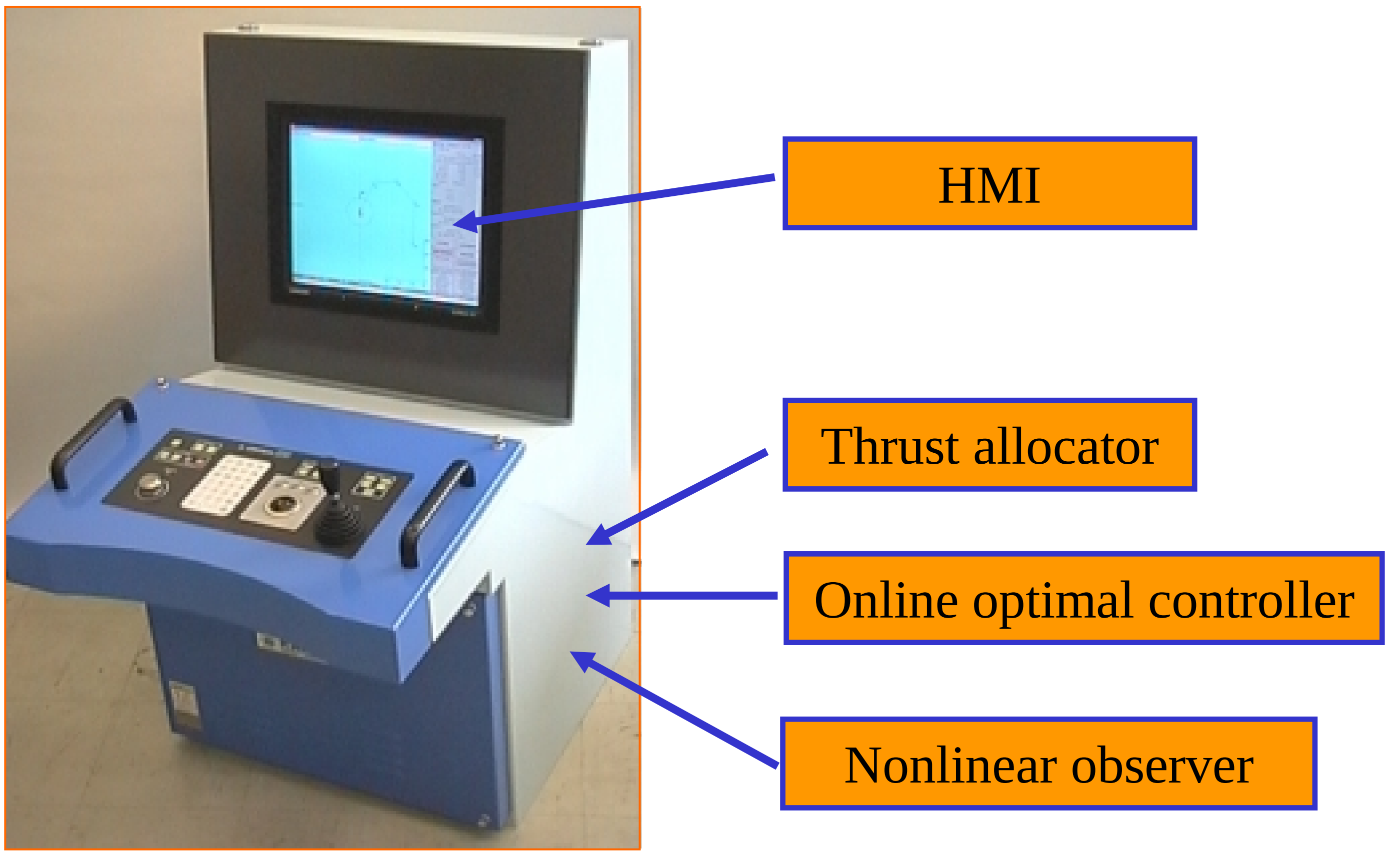
Kawasaki DPS “KICS-5000”



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“KICS-5000”

Review of the Optimal Control Problem

Controlled object (nonlinear model)

$$\dot{x} = f(x(t), u(t))$$

Unknown variables

Finite Time Cost function

$$J = \varphi(x(t+T)) + \int_t^{t+T} L(x(t'), u(t'))\, dt'$$

Hamiltonian

$$H(x, \lambda, u) = L(x, u) + \lambda^T f(x, u)$$

Euler-Lagrange equation (TPBVP)

Necessary Condition

$$\dot{x} = f,\ x(0) = x(t)$$

$$\dot{\lambda} = -H_x^T,\ \lambda(T) = \varphi_x^T(x(T))$$

$$H_u = 0$$

Online calculation (C/GMRES method)

Dr. Otsuka (Osaka Univ.)

Fast algorithm

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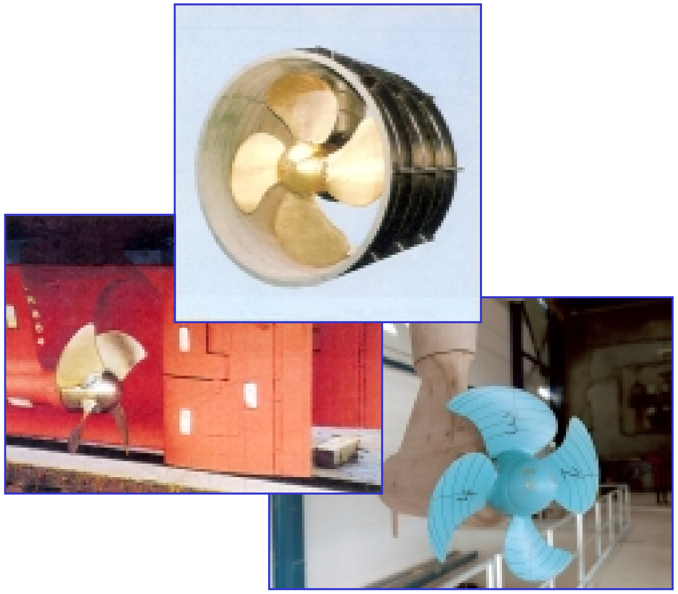

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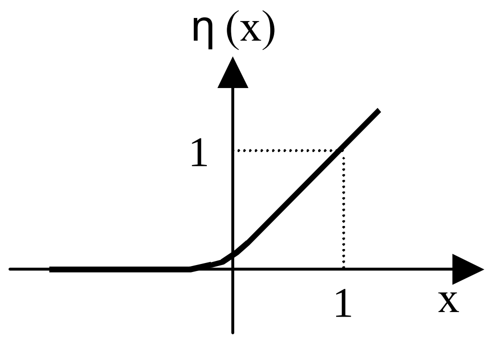
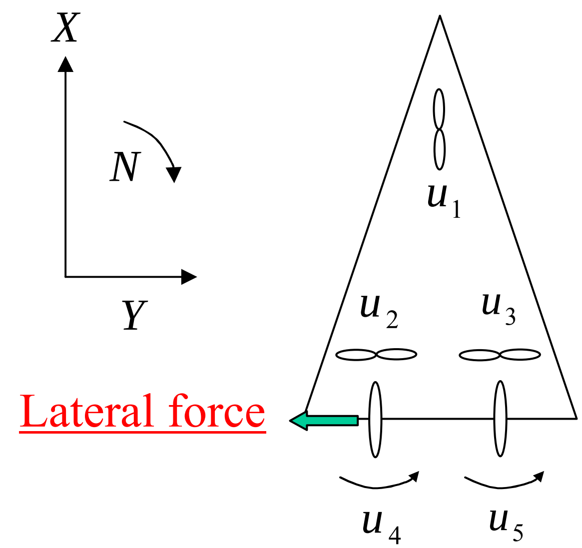
Thrust Allocation System with the Online Optimization

$$\eta(x) = \begin{cases} x & ; \quad x \geq 0 \\ 0 & ; \quad x < 0 \end{cases}$$



Thrust commands (given by a feedback controller)



Actuators

Thrust balance equations

$$\begin{cases} k_{11}u_2 + k_{12}u_3 = X \\ k_{21}u_1 - \{k_{22}\eta(u_2)u_4 + k_{23}\eta(u_3)u_5\} = Y \\ k_{31}u_1 + \{k_{32}\eta(u_2)u_4 + k_{33}\eta(u_3)u_5\} + (k_{34}u_2 - k_{35}u_3) = N \end{cases}$$

Nonlinear term

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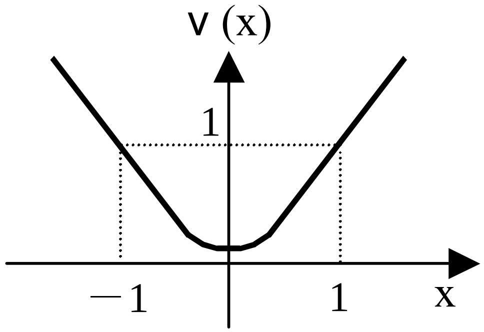
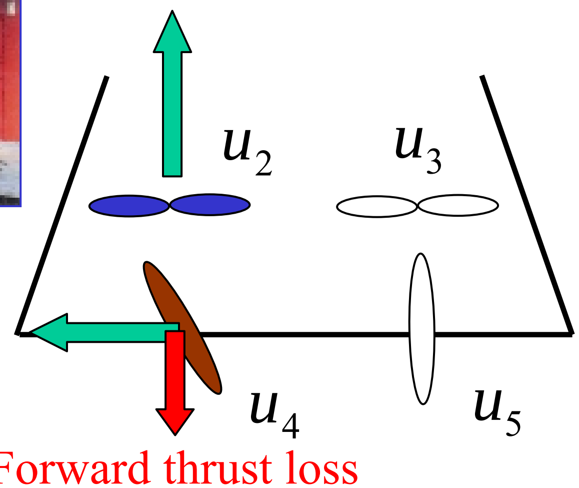
Thrust Allocation System with the Online Optimization

$$\nu(x) = |x|$$



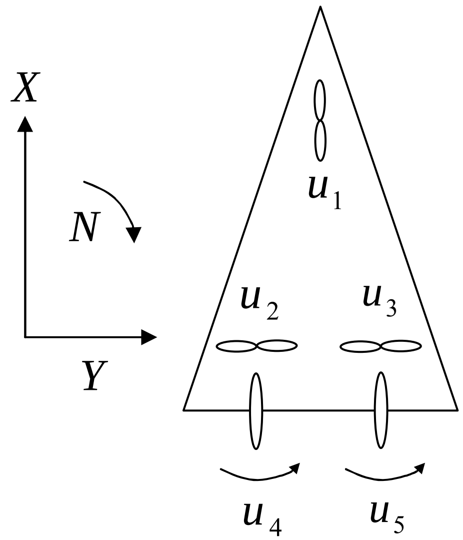


$$k_{11}u_2 + k_{12}u_3 = X$$

<u>Propeller and rudder interaction</u>

$$k_{11}\{u_2 - k_{r1}\eta(u_2)\nu(u_4)\} + k_{12}\{u_3 - k_{r2}\eta(u_3)\nu(u_5)\} = X$$

Optimization Problem Formulation



Cost function

$$J = \frac{1}{2}\sum_{i=1}^{5} r_i u_i^2$$

Hamiltonian

$$H = J + \lambda^T C$$

$$C = \begin{bmatrix} \mathrm{k}_{11}\{u_2 - k_{r1}\eta(\mathrm{u}_2)\nu(\mathrm{u}_4)\} + \mathrm{k}_{12}\{u_3 - k_{r2}\eta(\mathrm{u}_3)\nu(\mathrm{u}_5)\} - X \\ \mathrm{k}_{21}u_1 - \{k_{22}\eta(u_2)u_4 + k_{23}\eta(u_3)u_5\} - Y \\ \mathrm{k}_{31}u_1 + \{k_{32}\eta(u_2)u_4 + k_{33}\eta(u_3)u_5\} + (k_{34}u_2 - k_{35}u_3) - N \end{bmatrix}$$

Optimality condition

$$H_U = 0$$

Solve online by the C/GMRES method

$$\mathrm{U} = [\mathrm{u}_1 \quad \ldots \quad \mathrm{u}_5 \quad \lambda_1 \quad \lambda_2 \quad \lambda_3]^{\mathrm{T}}$$

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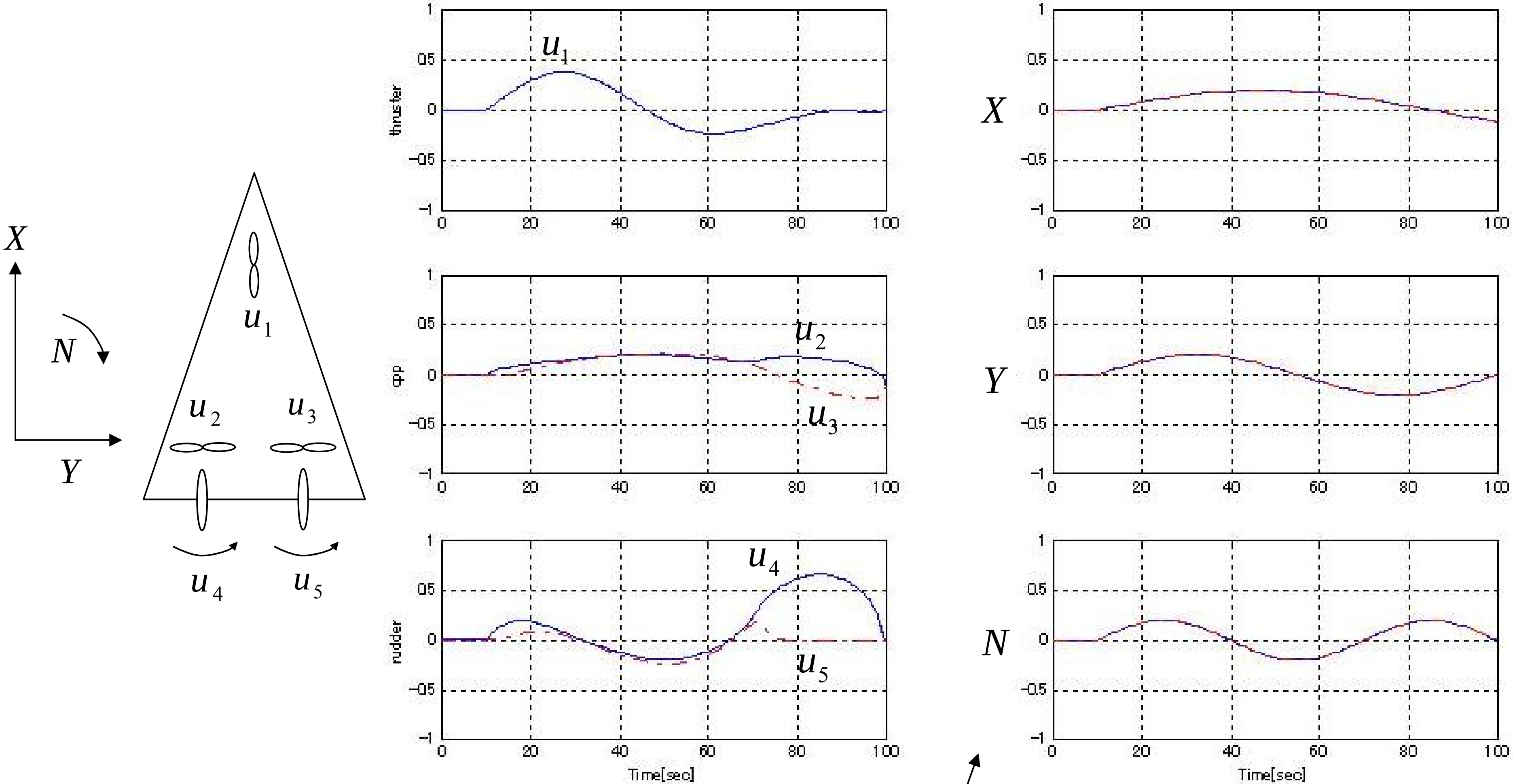
Algorithm Verification



Sinusoidal inputs

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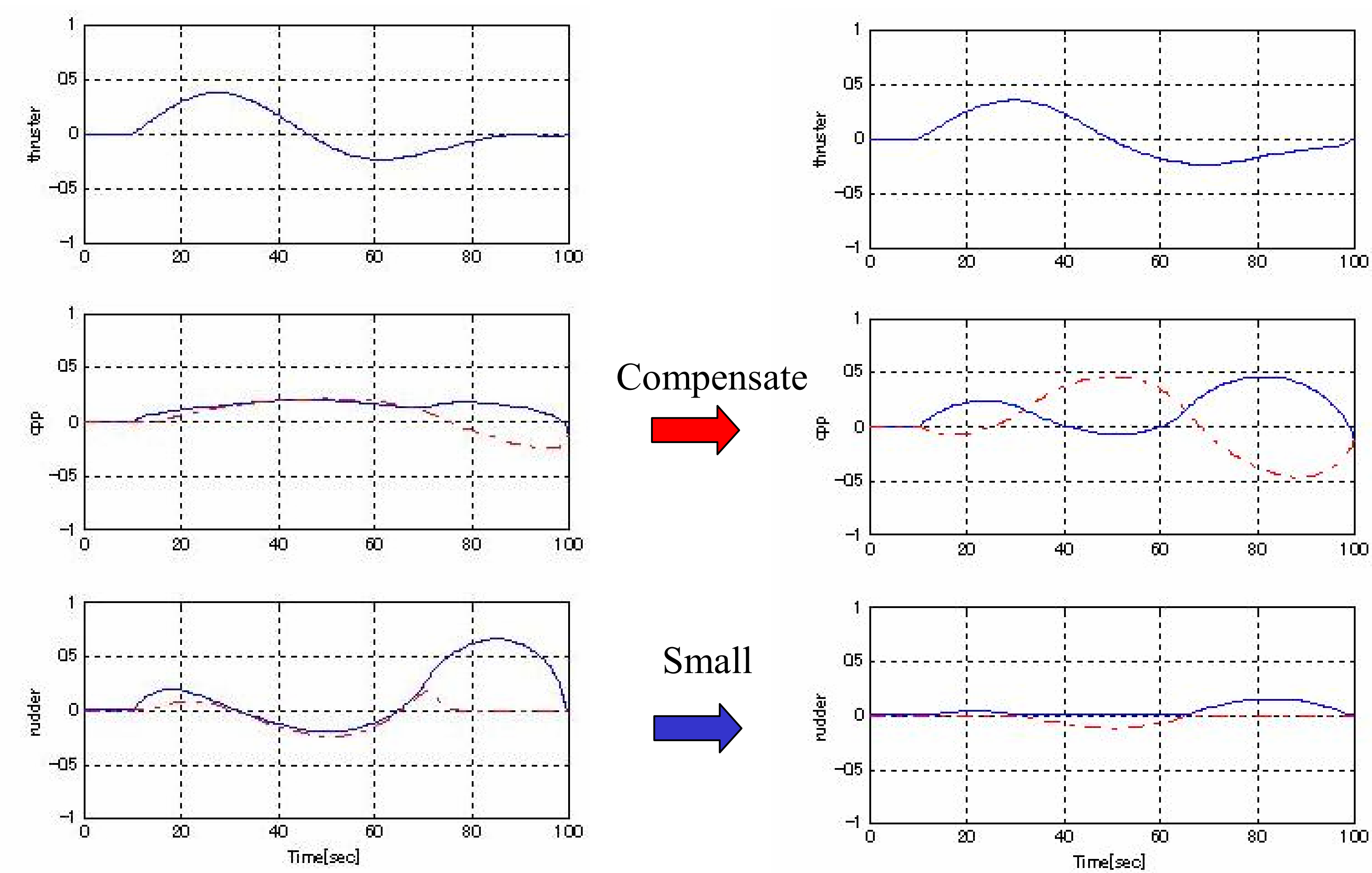
Algorithm Verification



$$J = \frac{1}{2}\sum_{i=1}^{3} r_i u_i + \frac{1}{2} r_4 u_4{}^2 + \frac{1}{2} r_5 u_5{}^2 \qquad r_4,\ r_5 \longrightarrow \underline{\text{Large}}$$

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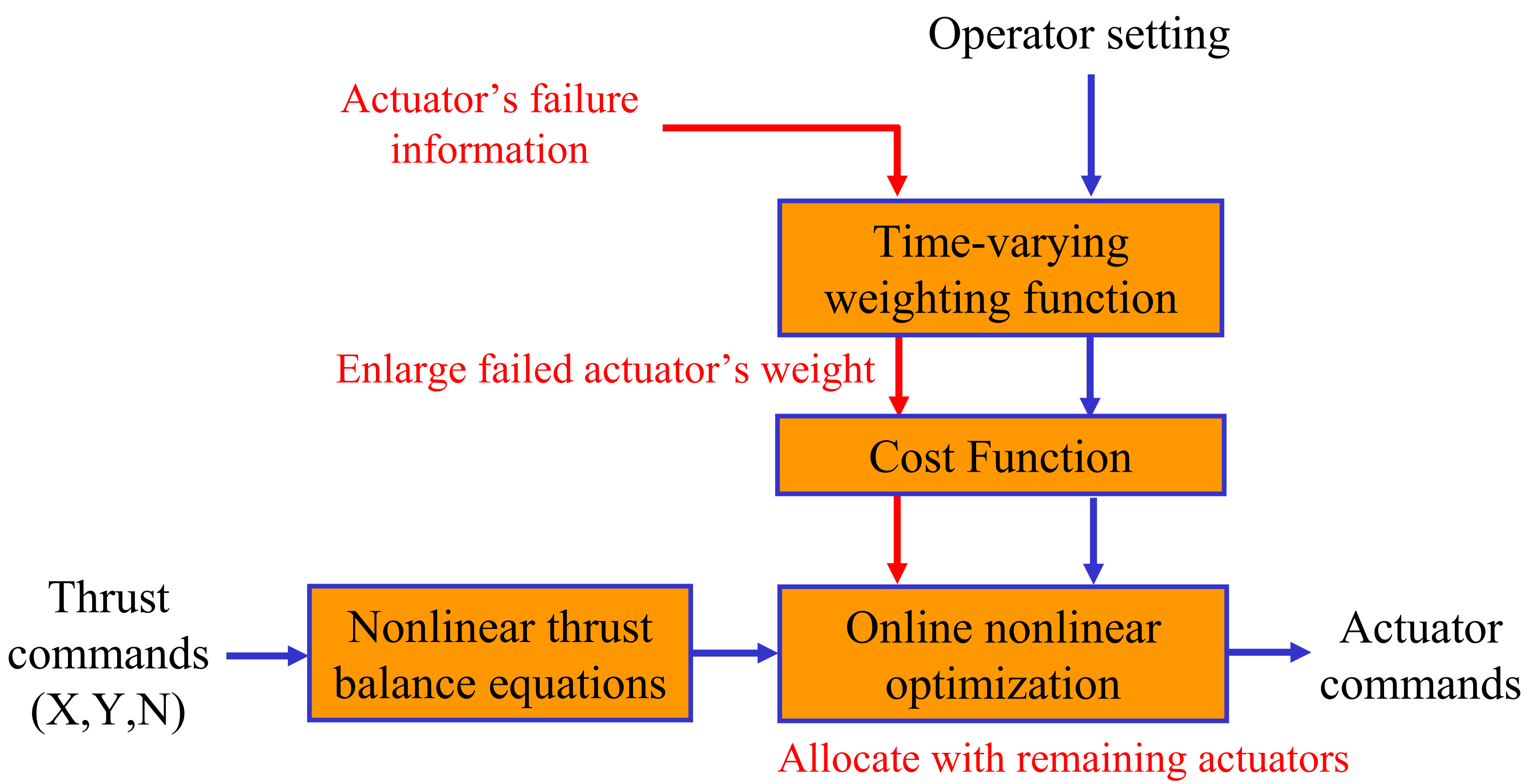
Online Thrust Allocation Algorithm



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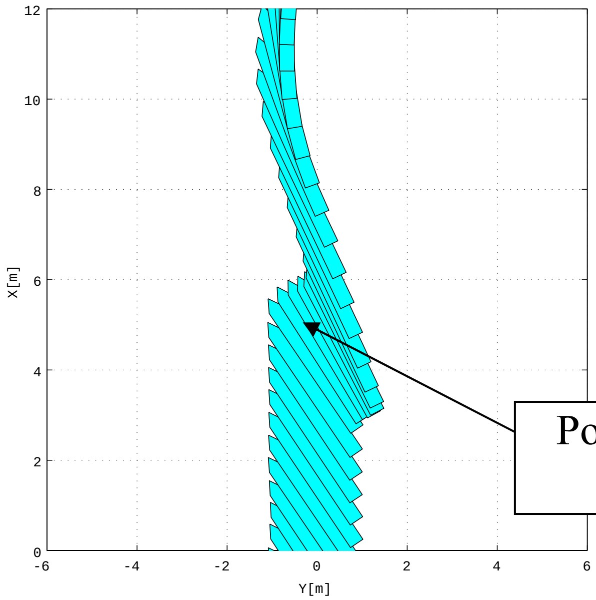
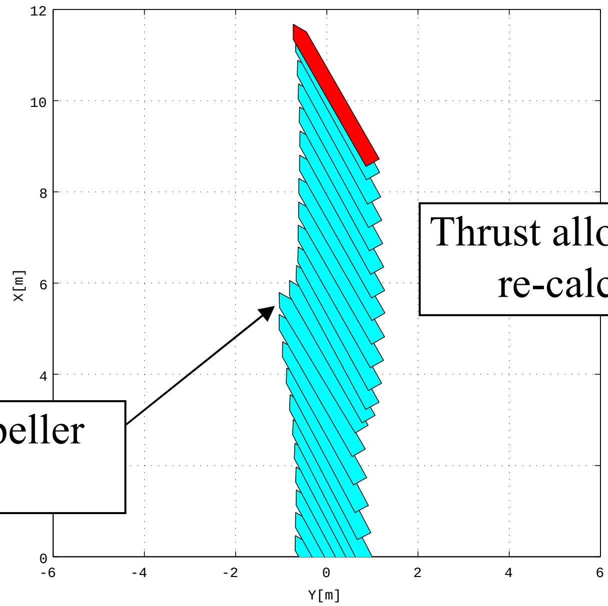
Effectiveness of Auto-rectification to Thruster Failure

Model ship

Conventional allocator



Optimal thrust allocator



Portside propeller stopped

Thrust allocation was re-calculated.

Route tracking test with keeping 30 degree between the ship's head and the moving direction.

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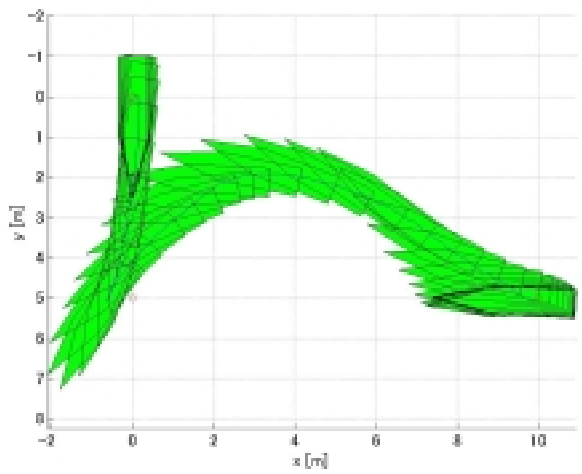

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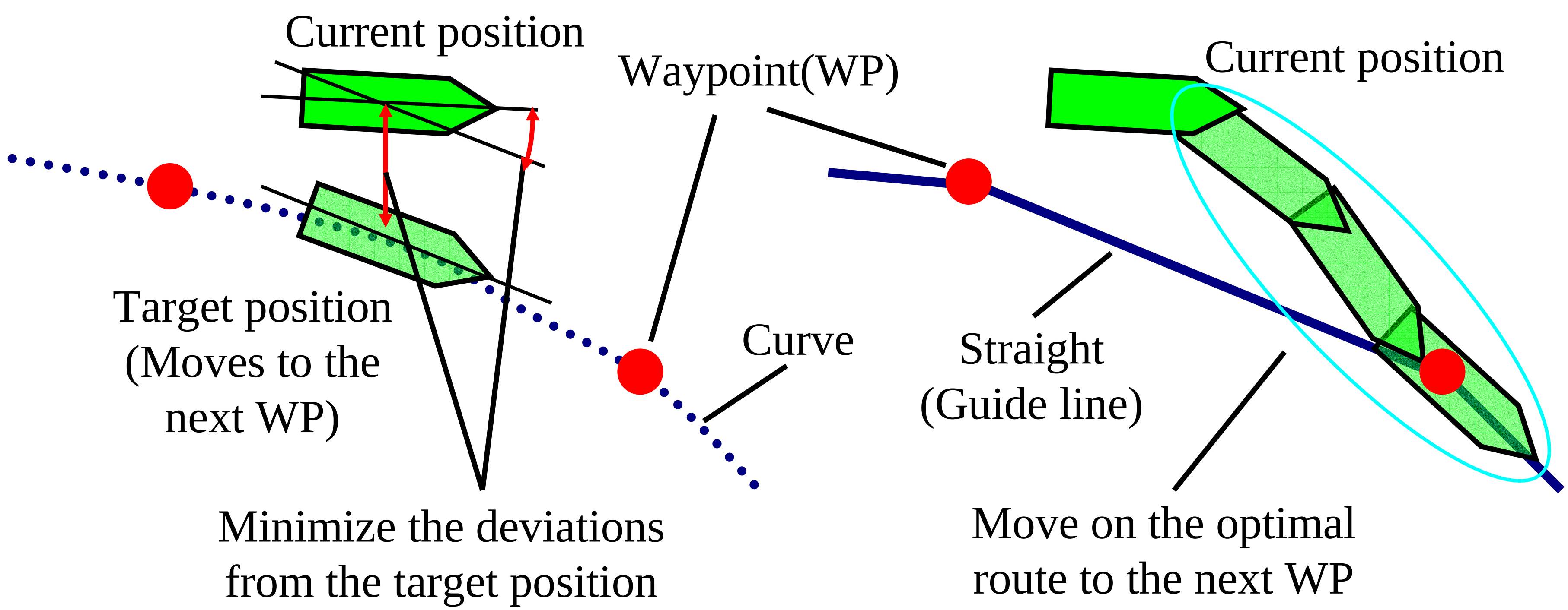
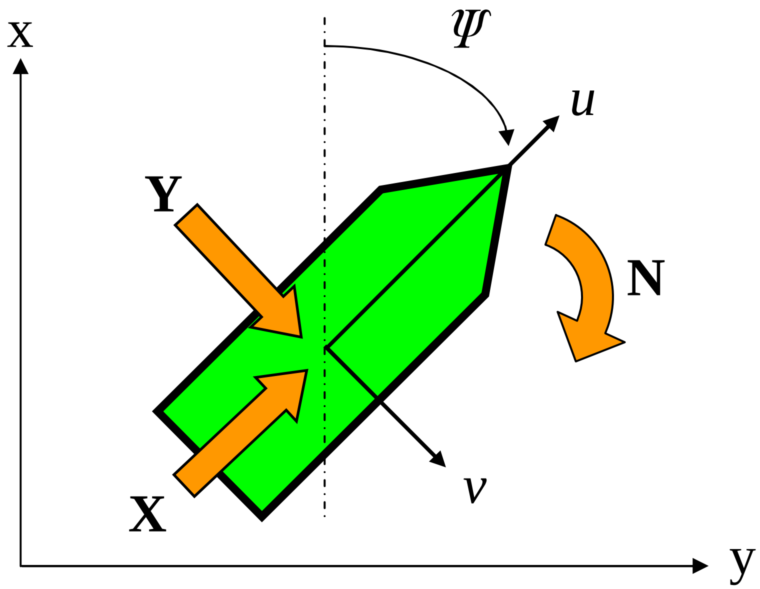
Comparison with Conventional Controller and Route Optimizing Controller

Conventional tracking control

Online nonlinear optimal control



State Variables



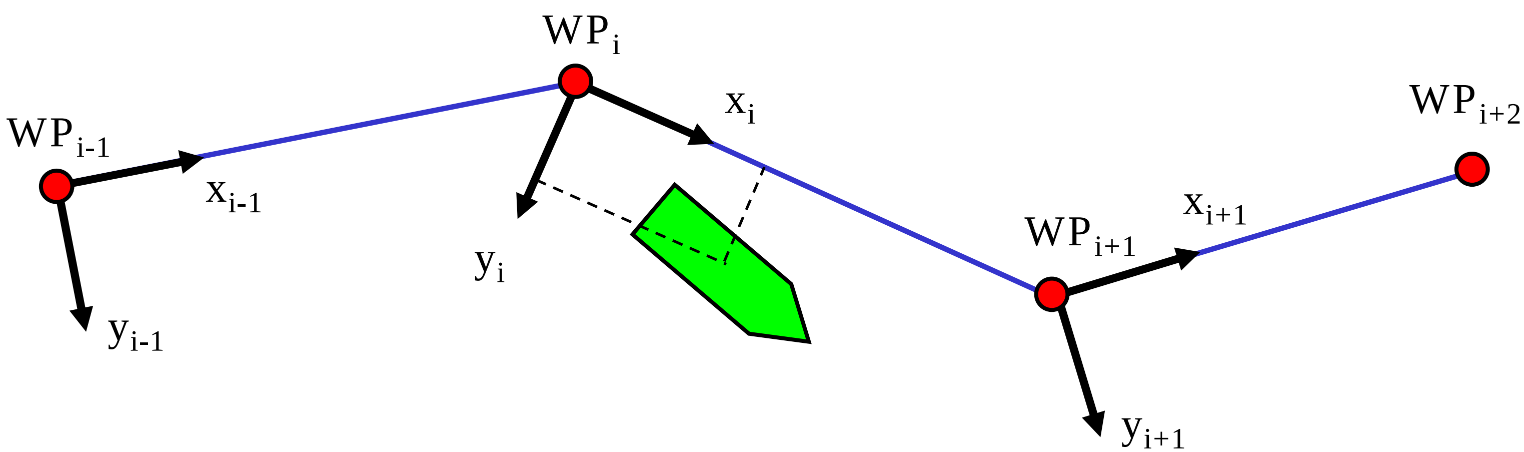
Hamiltonian

$$H = L + \lambda^T f$$

Constrained condition

(if any, user definition)

$$f = \begin{bmatrix} \dot{x} \\ \dot{u} \\ \dot{y} \\ \dot{v} \\ \dot{\psi} \\ \dot{r} \\ \dot{X} \end{bmatrix}$$



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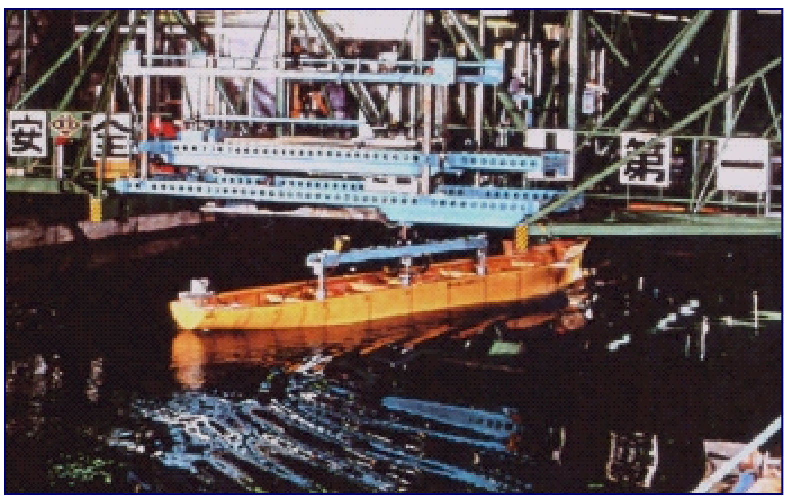
State Equations

$$f = \begin{bmatrix} \dot{x} \\ \dot{u} \\ \dot{y} \\ \dot{v} \\ \dot{\psi} \\ \dot{r} \\ \dot{X} \end{bmatrix} = \begin{bmatrix} u\cos\psi - v\sin\psi \\ M\,v\,r/(M+mx) + M\,x_G\,r^2/(M+mx) + (X+X_H)/(M+mx) \\ u\sin\psi + v\cos\psi \\ \{m_{33}(-M\,u\,r + Yr + Y_H) - m_{23}(-M\,x_G\,u\,r + Nr + N_H)\}/\det m \\ r \\ \{-m_{32}(-M\,u\,r + Yr + Y_H) + m_{22}(-M\,x_G\,u\,r + Nr + N_H)\}/\det m \\ -\dfrac{1}{Tx}X + \dfrac{Kx}{Tx}Xr \end{bmatrix}$$



Cross Flow Model
(KARASUNO Model)

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Cost Function

Cost function

$$J = \frac{1}{2}\left[\sum_{i=1}^{7} s_{fi} \left(x_{ref\ i} - x_i \right)^2 \right]_{t+T} +$$

$$\frac{1}{2} \int_t^{t+T} \left\{ \sum_{i=1}^{7} q_i \left(x_{ref\ i} - x_i \right)^2 + \sum_{i=1}^{3} r_i u_i^2 \right\} dt'$$

L

State variables

$[x \quad u \quad y \quad v \quad \psi \quad r \quad X]^T$

Thrusters

$[Xr \quad Yr \quad Nr]^T$

(Equivalent to power minimum)

Hamiltonian

$$H = L + \lambda^T f$$

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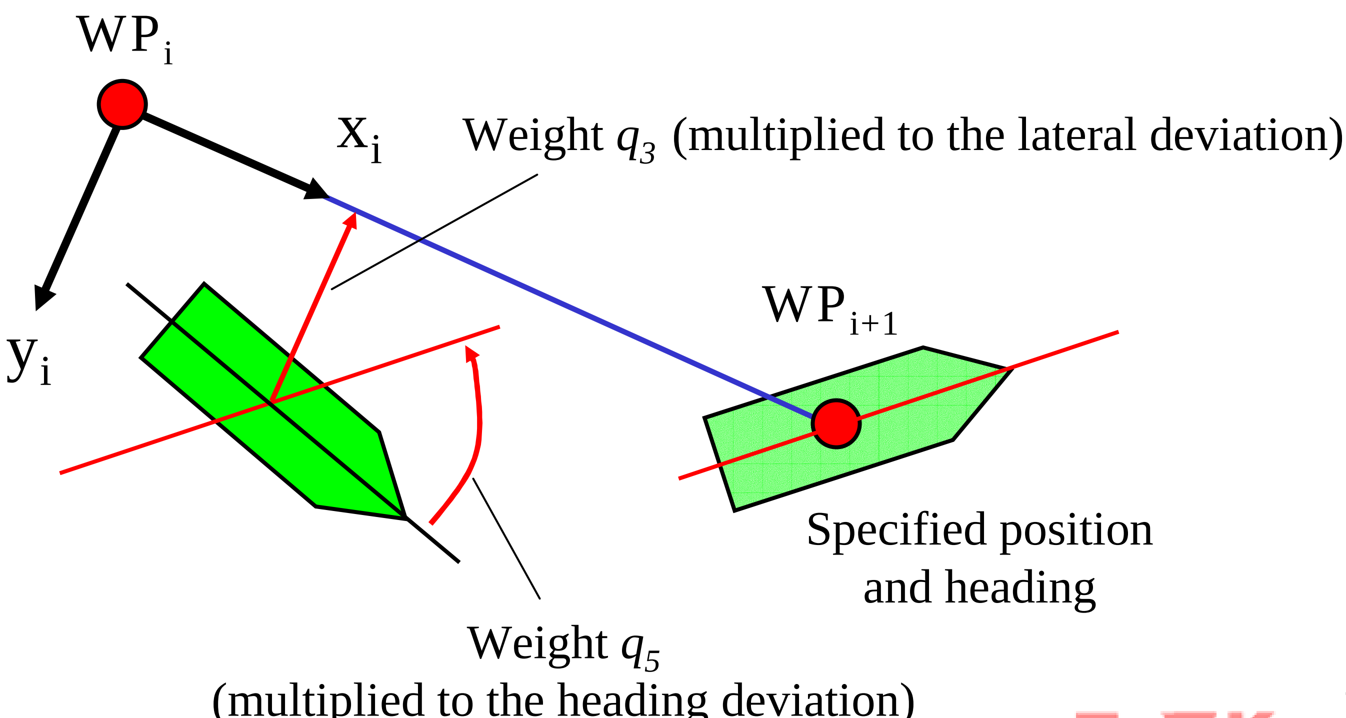
Route Tracking Results

$$J = \frac{1}{2}\left[\sum_{i=1}^{7} s_{fi}\left(x_{ref\,i} - x_i\right)^2 \right]_{t+T} + \frac{1}{2}\int_{t}^{t+T}\left\{ \sum_{i=1}^{7} q_i \left(x_{ref\,i} - x_i\right)^2 + \sum_{i=1}^{3} r_i u_i^{2} \right\} dt'$$

$$\left[x \quad u \quad y \quad v \quad \psi \quad r \quad X\right]^T$$



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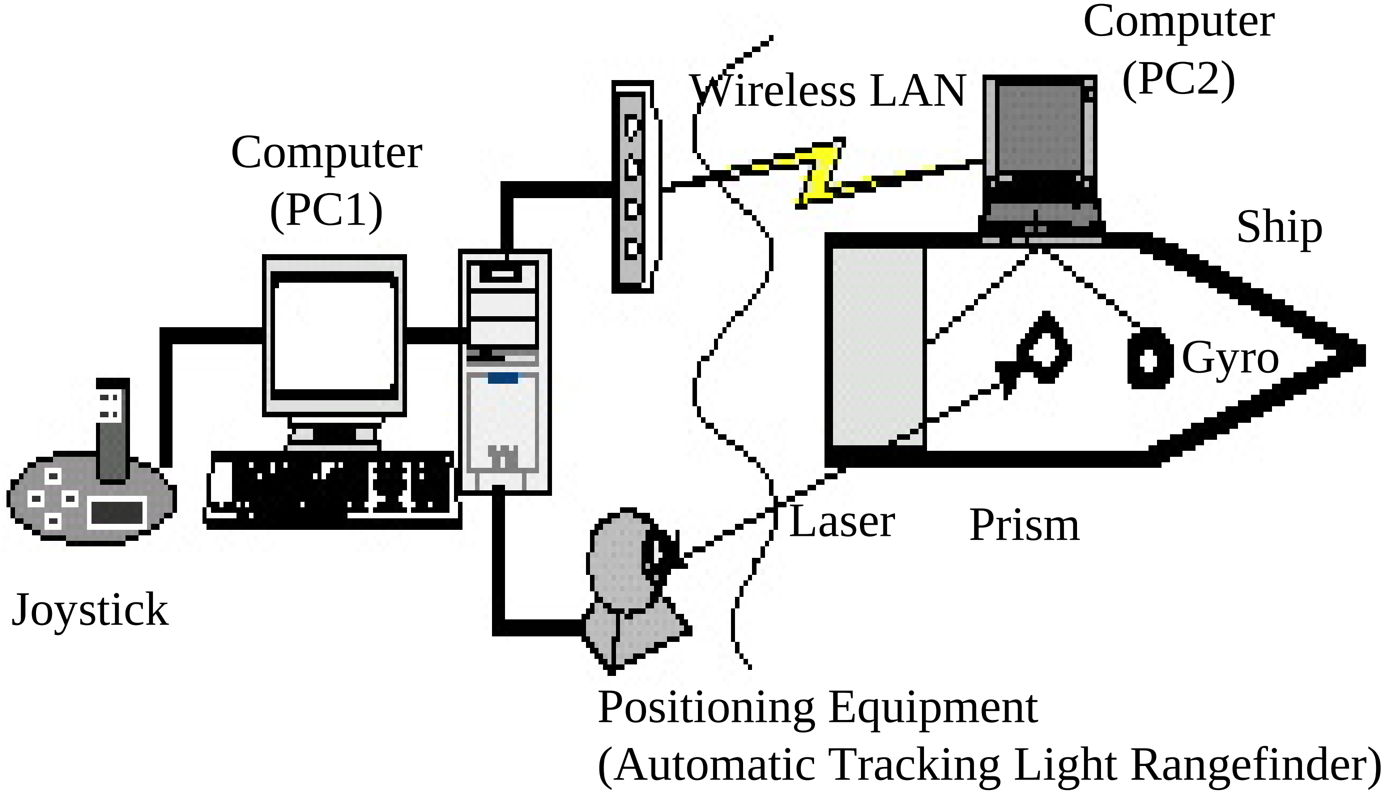
Configuration of Experimental Equipment



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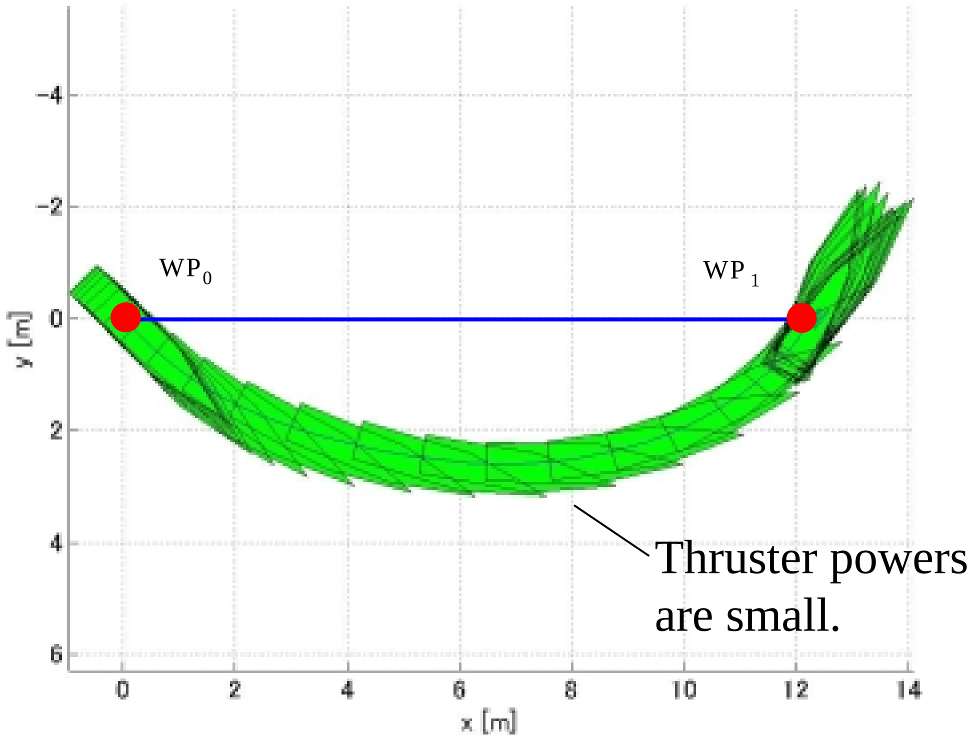
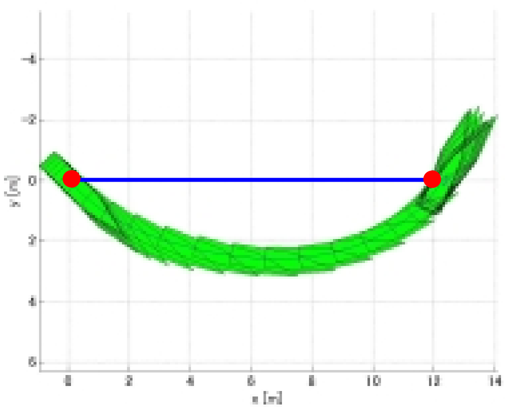
Example of model test result

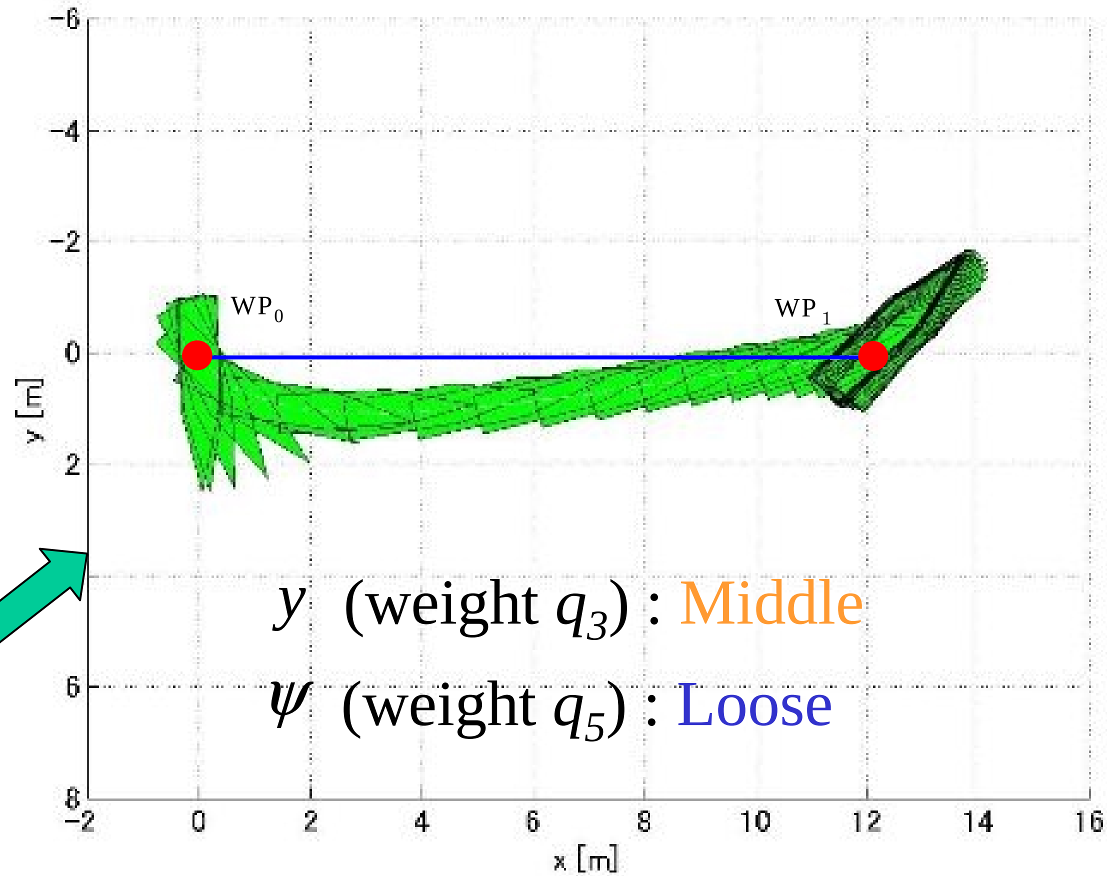


y (weight q_3) : Loose

ψ (weight q_5) : Loose

Example of model test result

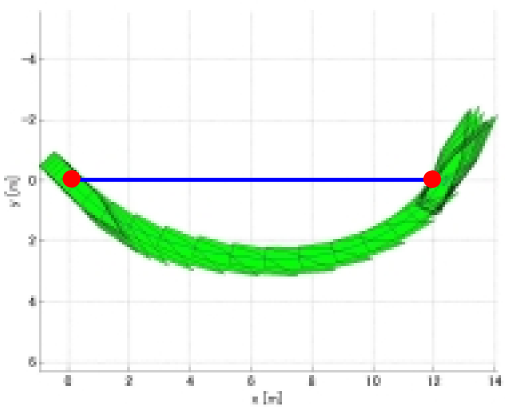


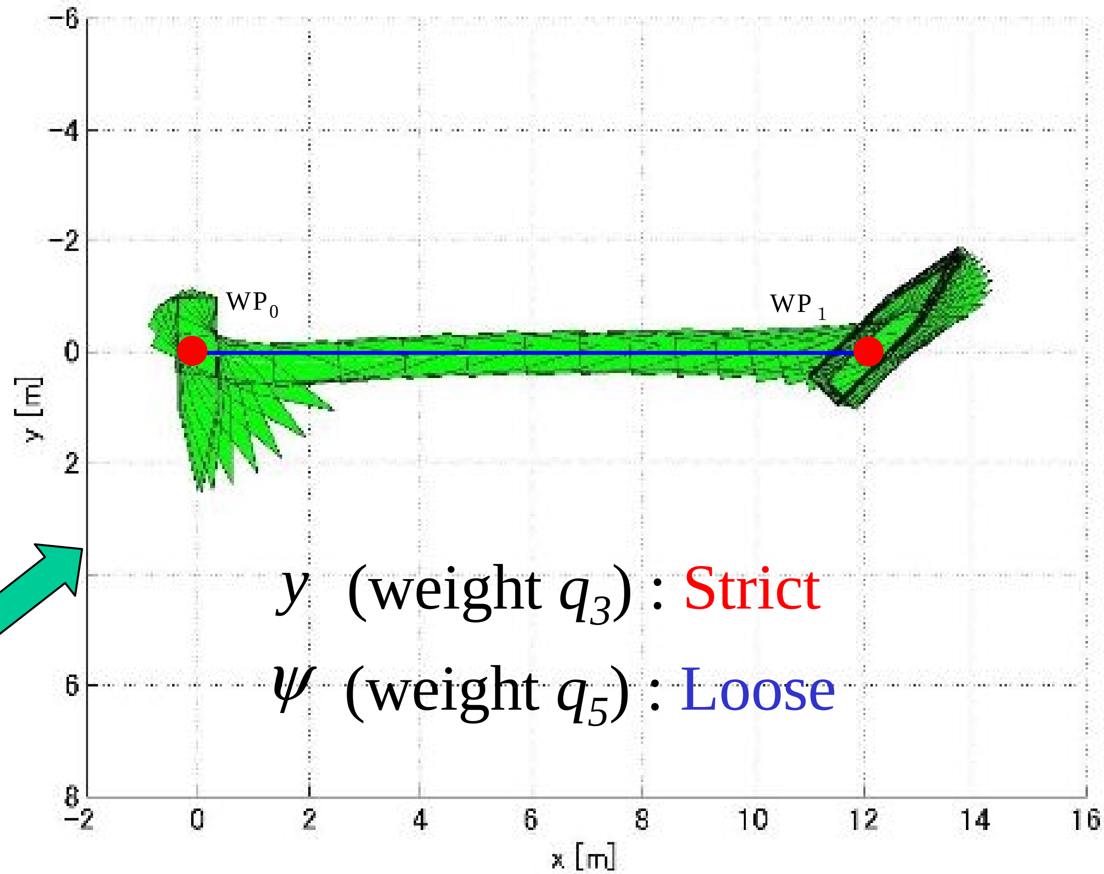


y (weight q_3) : Middle

ψ (weight q_5) : Loose

Example of model test result





y (weight q_3) : Strict

ψ (weight q_5) : Loose

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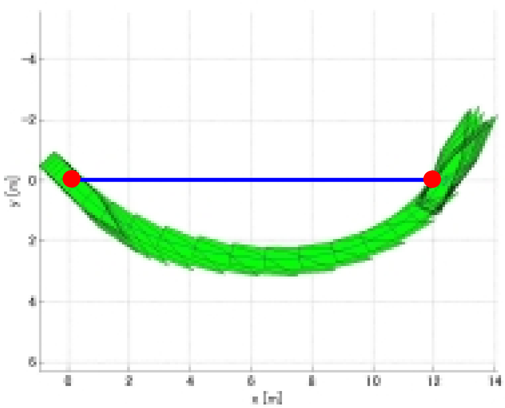
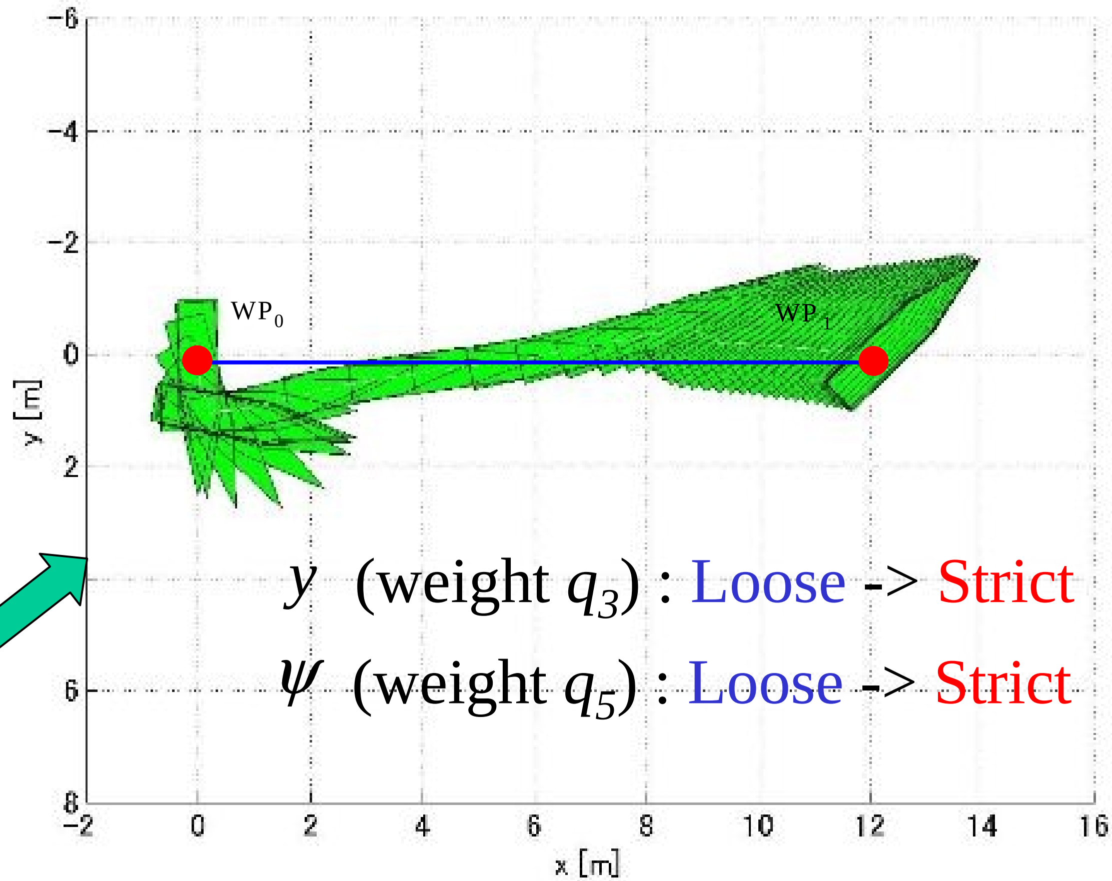
Example of model test result





y (weight q_3) : Loose -> Strict

ψ (weight q_5) : Loose -> Strict

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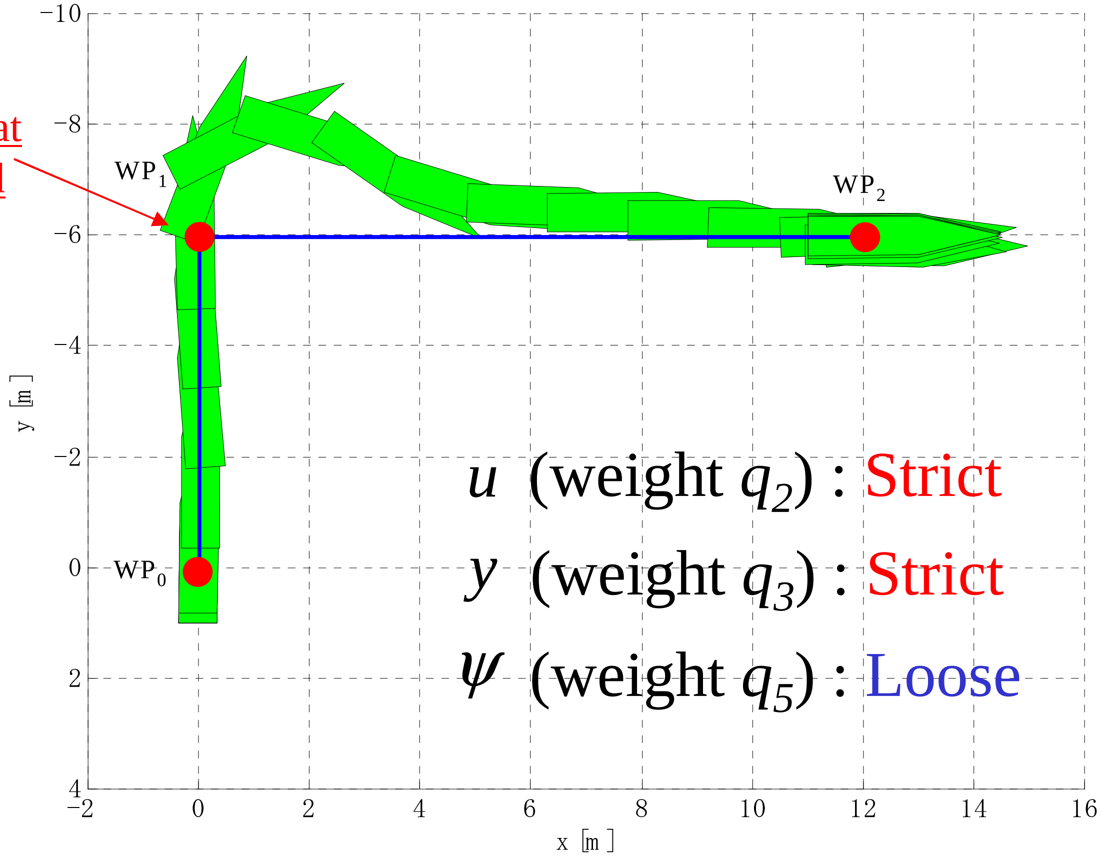
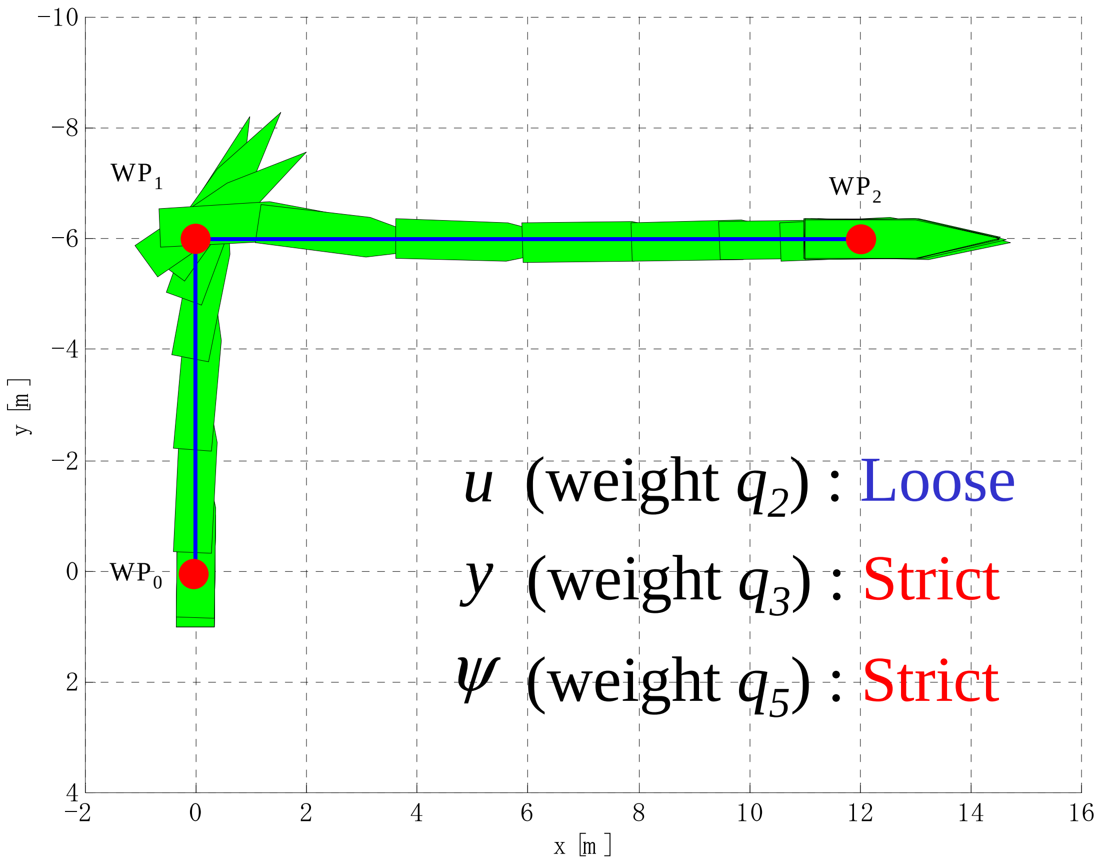
Example of simulation result

Pass on the WP1 at a Constant Speed



Right-angled Tracking

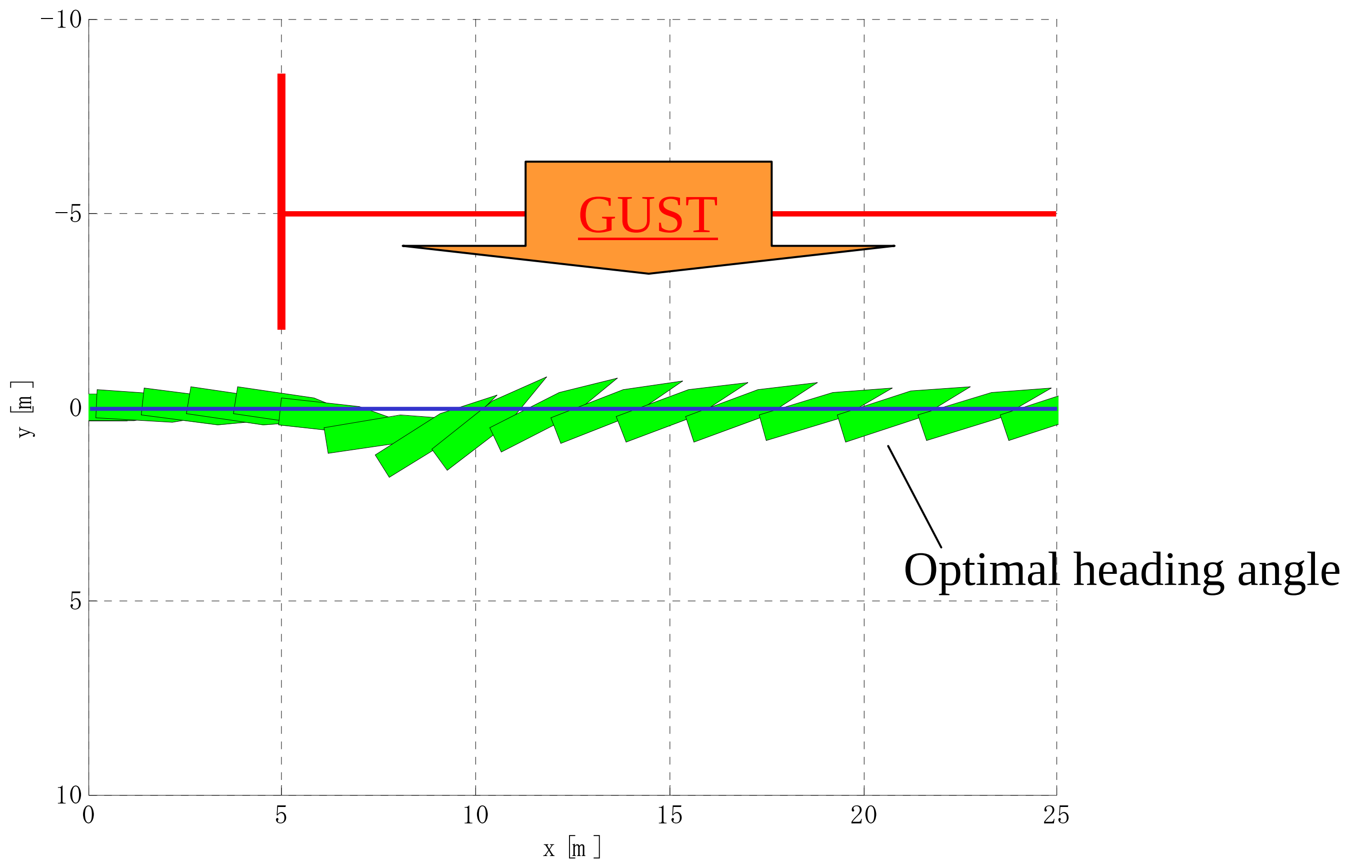
Example of simulation result



Right-angled Tracking

(Exact Tracking)

Example of simulation result



Straight Line Tracking

(Gust Case)

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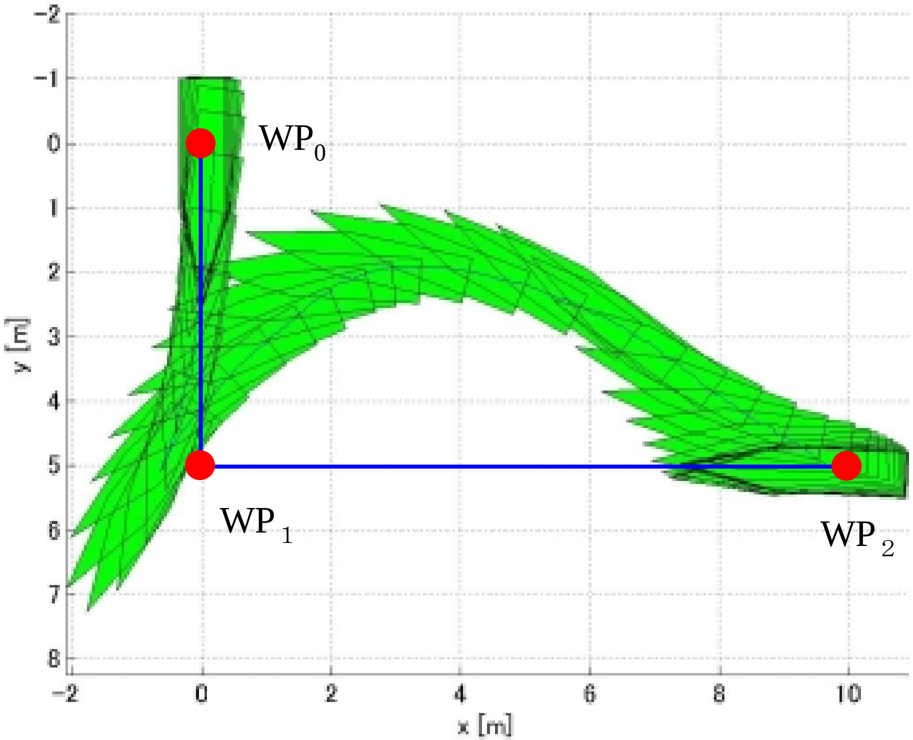
Example of model test result



Backward berthing test with three waypoints

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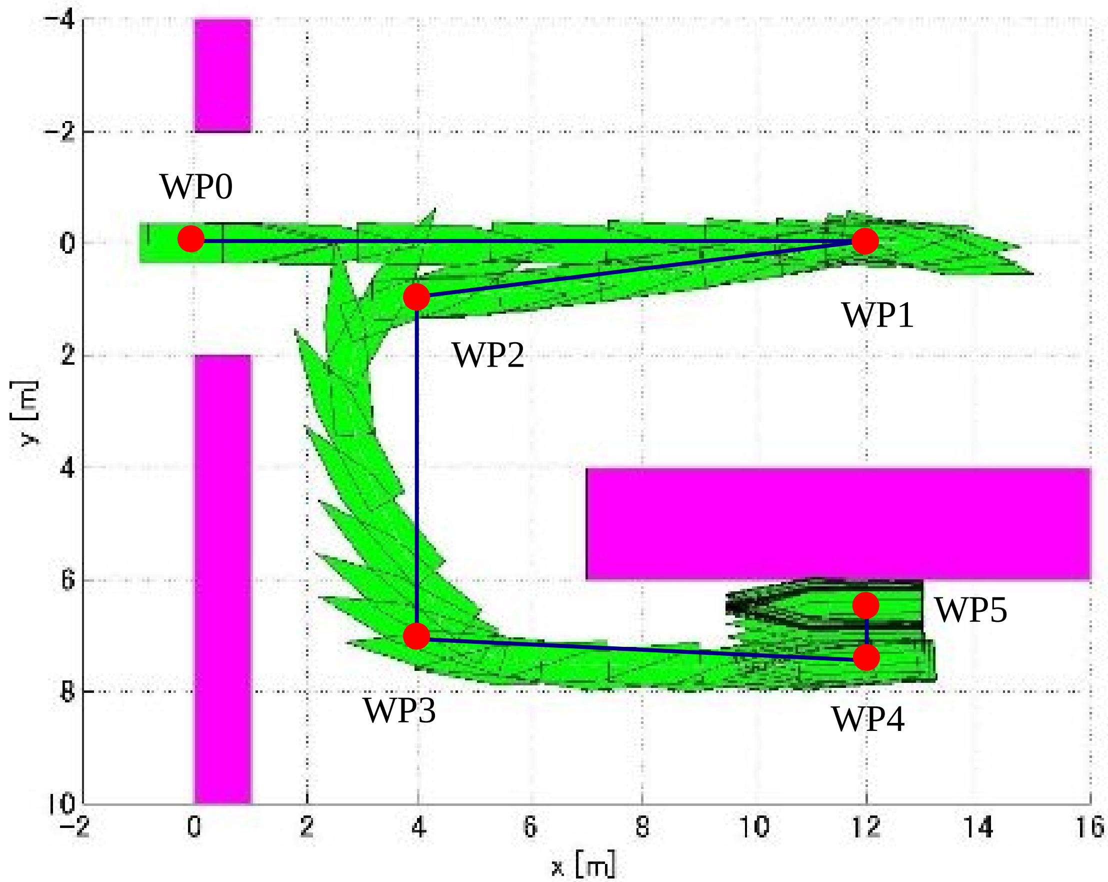
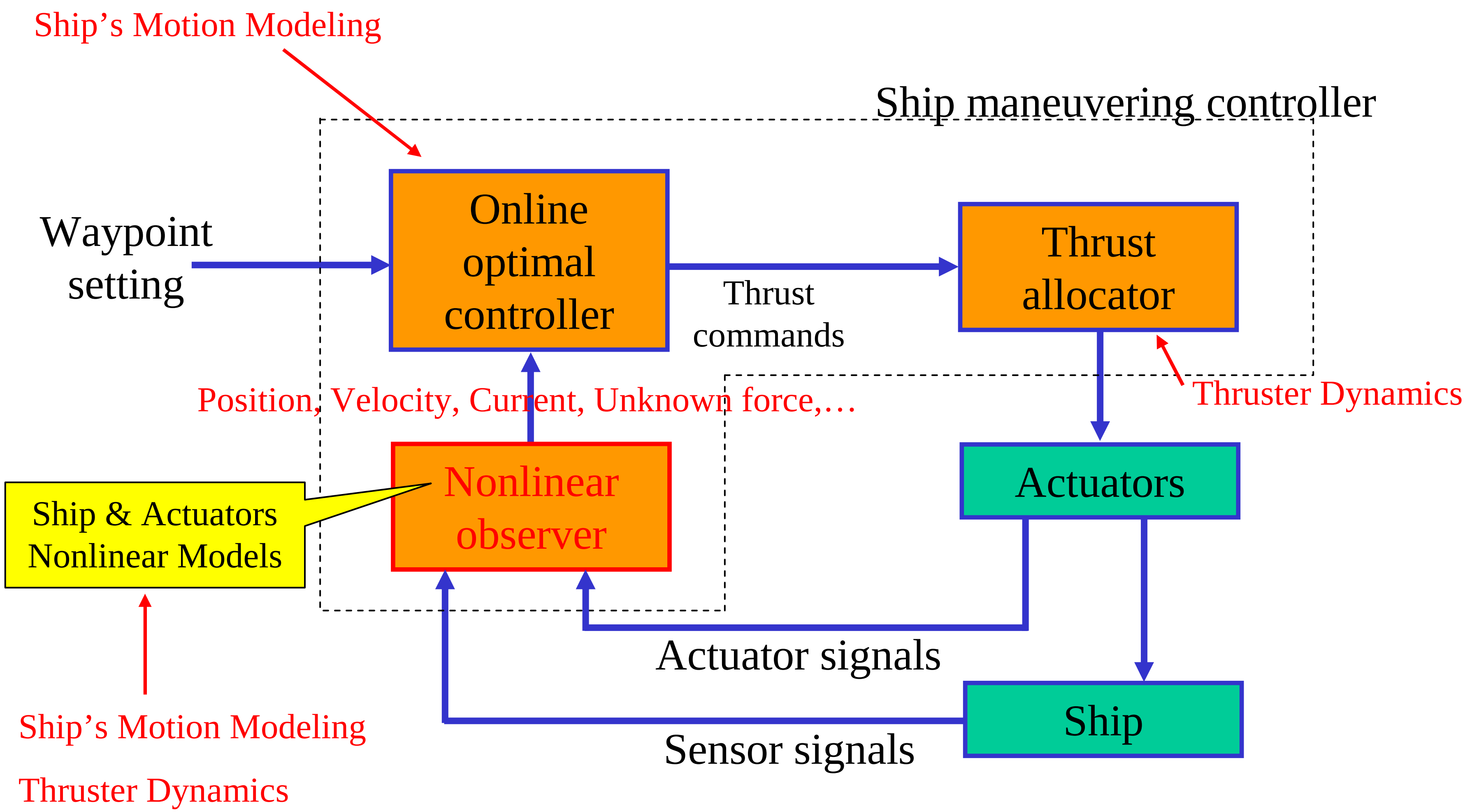
Example of model test result



Complicated berthing test with six waypoints

Nonlinear Observer (Dead Reckoning Function)



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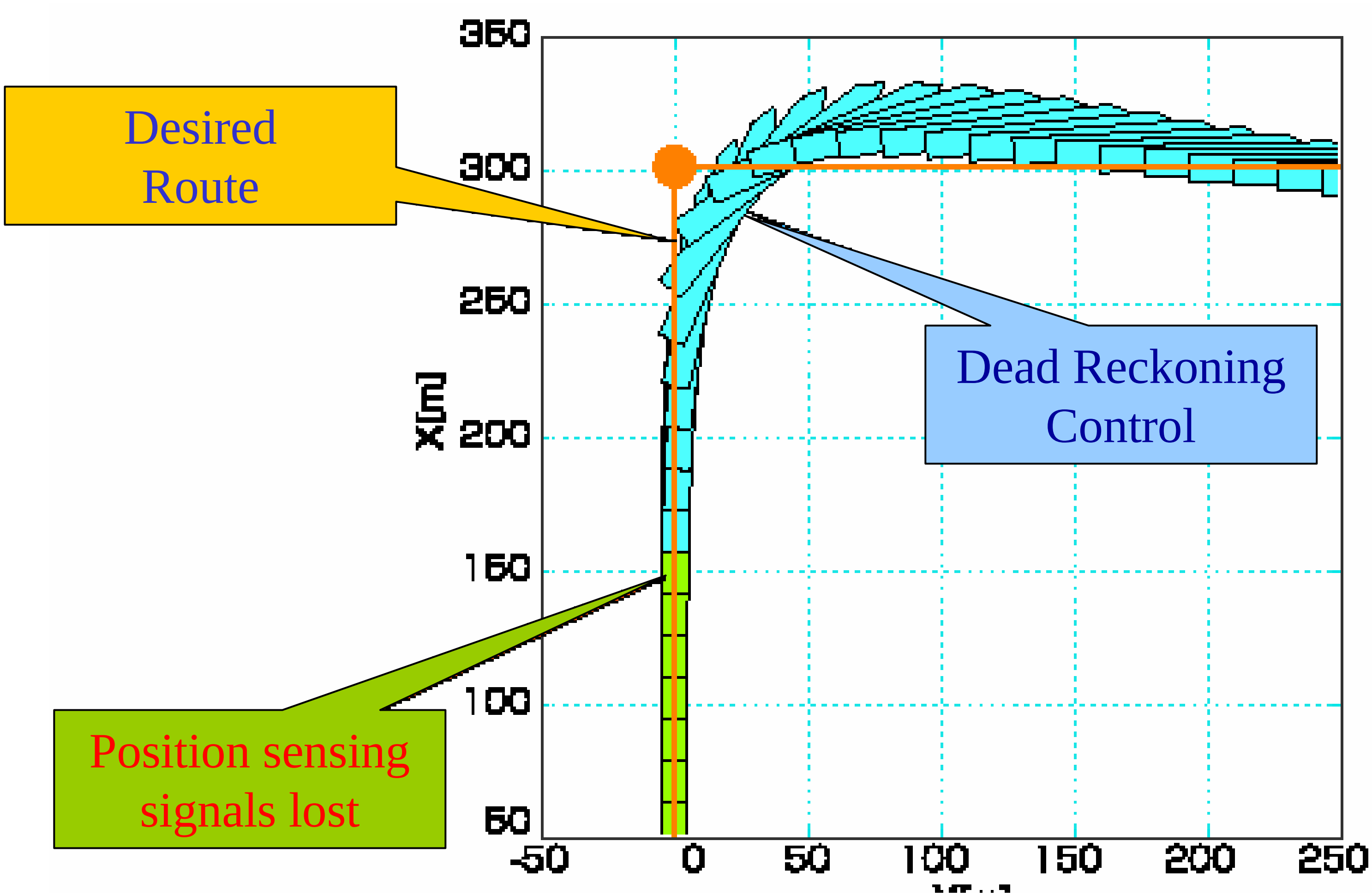
Nonlinear Observer (Dead Reckoning Function)



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Conclusion

Requirements for Ship Maneuvering Control System

- Online Optimization for Nonlinear Model
- Minimize Fuel Consumption
- Minimize Environmental Effects (Wind, Current, Waves, …)
- Auto-rectification to Thruster Failure
- Easy and Quick Route Planning

↓

Realizable berthing assistant system

Automatic optimal maneuvering and positioning

Ferries, LNG-FPSO, Work boat, …

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