Guidance, Navigation and Control of Unmanned Surface Vehicles (USVs)

—Doctoral Thesis Research Proposal

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Abstract

As there has been growing interest worldwide in commercial, scientific, and military issues of ocean and shallow waters, the demand for developing unmanned surface vehicles (USVs) with advanced guidance, navigation, and control (GNC) capabilities becomes more urgent. However, semi-autonomous USVs until now have been normally used rather than fully-autonomous USVs owing to numerous challenges, such as limited autonomy, sophisticated and hazardous environment, sensors and actuators and communication failures. Among all these challenges, the key challenge is the lack of fully-autonomous and reliable GNC techniques in face of different operating conditions and sophisticated environments. Further development of fully-autonomous USVs is strongly required so as to be less reliant on human interactions and subject to human errors. Besides giving an overall picture of the historical, current, and future progress of USVs, this research proposal in particular aims at outlining the research which is conducted to design and develop novel GNC schemes/strategies with applications to both individual and multiple USVs. In order to ensure their efficient and reliable performance under sophisticated and hazardous environments, this proposed research is intended to provide advanced levels of GNC capabilities to USVs. The schemes and strategies expecting from this research proposal are also verified by a series of simulations on the well-known USV benchmarks in the presence of disturbances, actuator saturation and different realistic fault scenarios.

Keywords: Unmanned surface vehicles (USVs); Guidance, navigation and control (GNC); Fault detection and diagnosis (FDD); Fault tolerant control (FTC); Linear parameter varying (LPV); Environmental disturbances; Actuator saturation; Actuator faults; Model uncertainties; Cooperative control.

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1 Introduction

Roughly two-thirds of the earth is covered by oceans [1], but comparatively little of this area has been thoroughly explored. Climate change, environmental abnormalities, personnel requirements, and national security issues have all led to a strong demand from commercial, scientific, and military communities for the development of innovative unmanned surface vehicles (USVs), also known as autonomous surface vehicles (ASVs) or autonomous surface crafts (ASCs). Despite this, only semi-autonomous USVs have normally been used rather than fully-autonomous USVs, owing to numerous challenges facing by the latter, such as limited autonomy due to the challenges in automated and reliable guidance, navigation and control (GNC) functions for all different operating conditions in face of sophisticated and hazardous environments, and sensor, actuator and communication failures. Further development of fully-autonomous USVs is required in order to minimize both the need for human control and the effects to the effective, safe and reliable USVs operation due to human errors [2].

The development and use of USVs are expected to contribute to tremendous benefits, such as lower developing and running costs, improved personnel safety and security, extended operational range and precision, greater autonomy, increased flexibility in sophisticated environment, as well as dirty, dull, harsh, and dangerous missions [3].

The remainder of this proposal is organized as follows: Section 2 briefly introduces background, motivation, and literature review of GNC techniques for USVs. Section 3 discusses the thesis scope and objectives. Section 4 outlines the applied research methodologies. Section 5 draws the timeline for appropriate completion of the proposed thesis. Section 6 presents the conclusion and future work. The research progress to date is illustrated in the appendix.

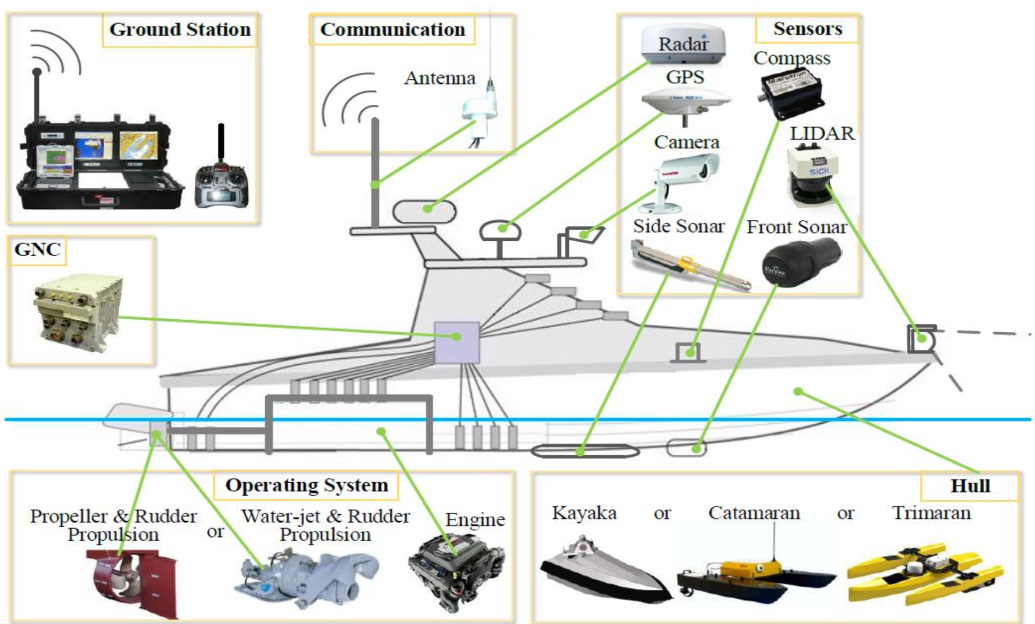


Figure 1: Fundamental architecture of a typical USV.

2 Background, Motivation, and GNC Review

2.1 Background

Depending on practical applications, USVs may come in a variety of appearances and functionalities. However, there are several basic elements that must be included in every USV (see Fig. 1):

hull and auxiliary structural elements; power, operating systems, and associated subsystems; GNC systems; communication systems; data collection equipment; ground station.

2.2 Motivation

With the aid of more effective, compact, and commercially available and affordable navigation equipment, including GPS and IMUs, as well as more powerful and reliable wireless communication systems [9], greater opportunities have been provided for USVs and their applications than ever before. USVs can be developed for a wide range of potential applications (as listed in Table 1) in a cost-effective way, such as scientific research, environmental missions, ocean resources explorations, military utilization, and other applications.

Table 1: Potential applications of USVs

Types	**Specific Applications**
Scientific research	Bathymetric survey [3]; ocean biological phenomena, and migration and changes in major ecosystems [10]; ocean activities research; multi-vehicle cooperation (cooperative work among aerial, ground, water surface or underwater vehicles) [11]; as experimental platforms for the purpose of testing hull designs, communication and sensor equipments, propulsion and operating systems.
Environmental missions	Environmental monitoring, samplings and assessment [6]; disaster (like tsunami, hurricane, eruption of submarine volcano) aided prediction and management, and emergency response [12]; pollution measurements and clean-up.
Ocean resources explorations	Oil, gas and mine explorations [3]; offshore platform/pipeline construction and maintenance [16].
Military utilization	Port, harbor, and coastal surveillance, reconnaissance and patrolling [13]; search and rescue [3, 12]; anti-terrorism/force protection [2]; mine countermeasures; remote weapons platform [14]; target drone boats [3].
Other applications	Transportation [15]; mobile communication relays [17]; refueling platform for USVs, unmanned aerial vehicles (UAVs), unmanned underwater vehicles (UUVs), and other manned vehicles.

USVs are always in competition with other manned or unmanned systems in terms of some specific applications [18]. Table 2 provides a brief comparison of these systems. All the above-mentioned results indicate the increasing demand of USVs in riverine/maritime applications. Despite this, the riverine/maritime environment is normally sophisticated and hazardous, which presents tremendous challenges, such as environmental disturbances from wind, waves and currents, potential collision from surrounding, and variation of environmental conditions. Besides these issues, USVs inevitably encounter variety of challenges from themselves, such as system faults (including sensors, actuators and communication faults), model uncertainties, and state and actuator constraints. These phenomena exactly motivate the design and implementation of more reliable, available, and cost-effective GNC techniques for developing fully-autonomous USVs.

2.3 Brief Review on Applications of GNC to USVs

The purpose of this subsection is to give a brief overview of guidance, navigation, and control systems, including their basic concepts and available references.

Table 2: Performance attributes comparison of USVs and other vehicles

● Clear advantage of USVs ◐ Near parity ○ Clear disadvantage of USVs

Attributes	UUVs	Float Platforms	Satellites	Manned Ships	UAVs	Manned Aircrafts
Endurance	●	○	○	◐	●	●
Payload capacity	●	◐	●	◐	●	◐
Cost	◐	○	●	◐	●	◐
Maneuverability	●	●	●	●	○	●
Deployability	●	●	●	●	○	●
Water depth measurement	○	◐	●	◐	●	◐
Autonomy requirement	◐	●	●	●	◐	●

2.3.1 Relationships among USV Subsystems

As indicated in Fig. 2, the autonomous operation of USVs generally constitutes three fundamental elements: guidance, navigation, and control subsystems [19–21]. They work in interaction with each other, imperfection in one subsystem may degrade the performance of the whole system.

1. *Guidance system* is responsible for continuously generating and updating smooth, feasible, and optimal trajectory commands to the control system according to the information provided by the navigation system, assigned missions, vehicle capability, and environmental conditions.

2. *Navigation system* concentrates on identifying the USV's current and future states (such as position, orientation, velocity, and acceleration), and its surrounding environment based on the past and current states of the USV as well as environmental information obtained from its onboard sensors.

3. *Control system* focuses on determining the proper control forces and moments to be generated in conjunction with instruction provided by the guidance and navigation systems, while at the same time satisfying desired control objectives.

2.3.2 Applications of GNC to USVs

1. *Guidance*: A feasible guidance system is an essential component for increasing USVs autonomy level, while more advanced guidance capabilities are required to accomplish tasks under more complicated and strict constraints, including poorly mapped environments and real-time computational requirement [20, 22]. To give a basic understanding of the current research interests on USVs guidance systems, a brief classification is illustrated in Fig. 3.

2. *Navigation*: The safe and efficient control of USVs depends heavily on an appropriate navigation system with sensing, state estimation, environment perception, and situation awareness capabilities. The existing USV navigation techniques are briefly reviewed in Fig. 4.

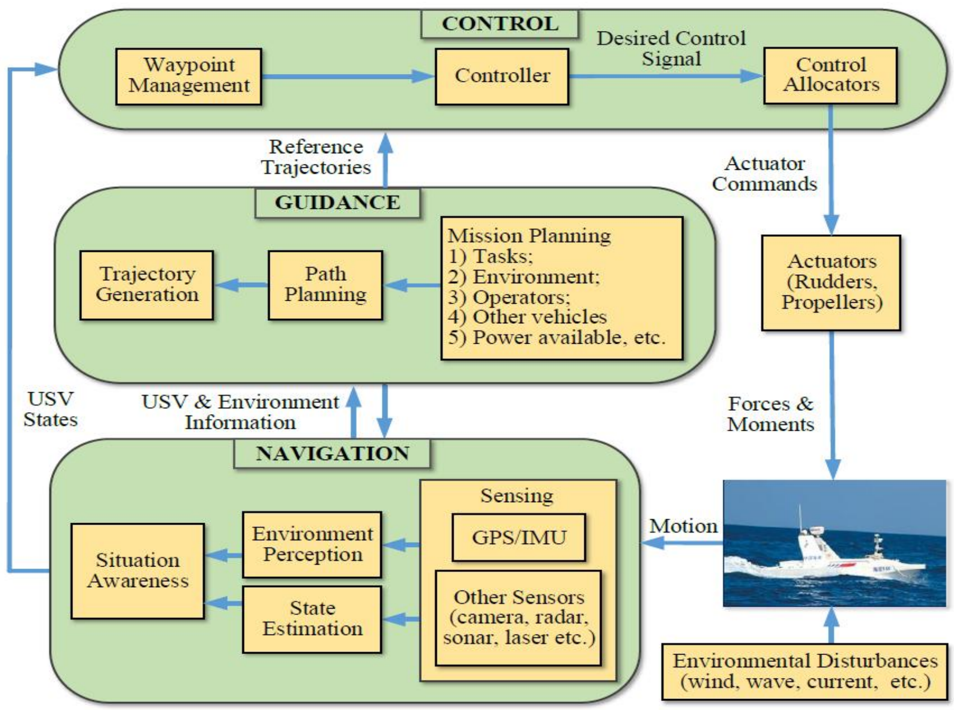


Figure 2: General structure of USV guidance, navigation, and control systems.

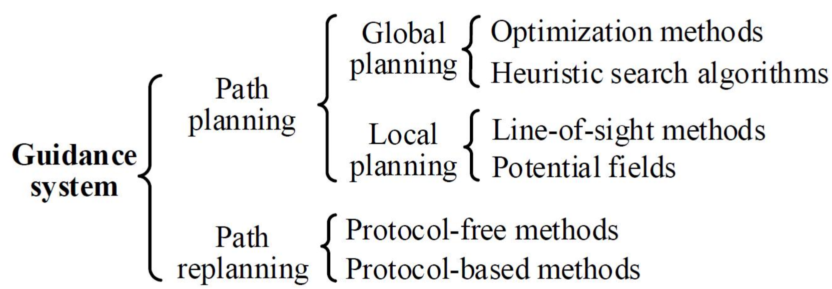


Figure 3: Classification of USV guidance systems with respect to functions and methods.

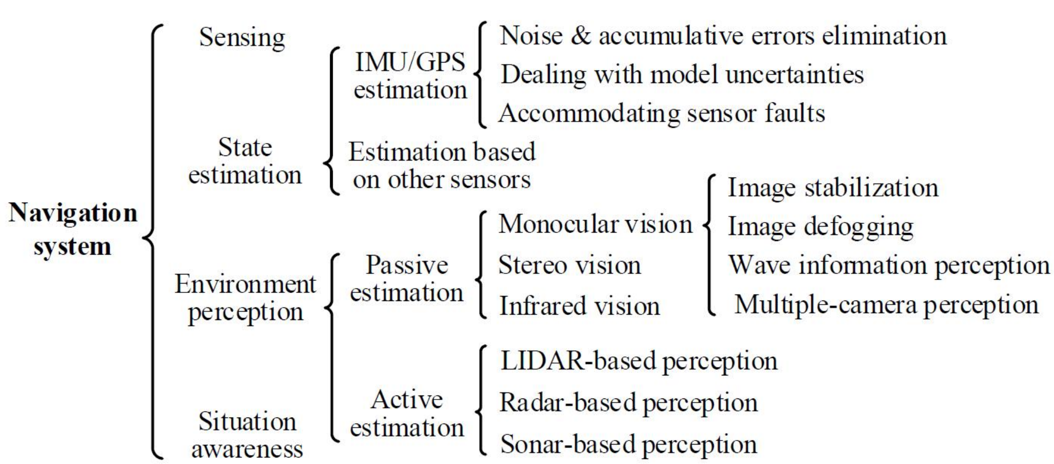


Figure 4: Classification of USV navigation systems with respect to functions and methods.

Table 3: Classification of challenges in USV control systems

Experiment	Disturbances	Uncertainties	System Faults	Constraints
$\surd$	$\surd$	$\surd$	$\times$	$\surd$
$\surd$	$\surd$	$\surd$	$\times$	$\times$
$\surd$	$\surd$	$\times$	$\surd$	$\times$
$\surd$	$\surd$	$\times$	$\times$	$\surd$
$\surd$	$\surd$	$\times$	$\times$	$\times$
$\surd$	$\times$	$\times$	$\times$	$\surd$
$\surd$	$\times$	$\times$	$\times$	$\times$
$\times$	$\surd$	$\surd$	$\times$	$\times$
$\times$	$\surd$	$\times$	$\times$	$\surd$
$\times$	$\surd$	$\times$	$\times$	$\times$
$\times$	$\times$	$\surd$	$\times$	$\times$
$\times$	$\times$	$\times$	$\times$	$\surd$

Note: ($\surd$) considered; ($\times$) not considered.

3. *Control*: USVs may diverge from the predefined path due to not only poor control design strategies, but also environmental disturbances, model uncertainties (unmodelled dynamics and parameters), actuator saturation, strong couplings, underactuation, and system faults (faults of sensors, actuators and communication devices). Currently, majority of the existing work only focuses on USVs control without consideration of the above-mentioned factors. The control design for such nonlinear system remains a challenging issue. Table 3 briefly identifies the current research that considers the above-mentioned challenges.

3 Scope and Objectives

This research aims to design and develop novel GNC schemes with application to USVs at both single agent and multiple agents levels. The proposed research plan in particular is organized around the following objectives:

1. Design and develop online model-based disturbance estimation techniques which can effectively estimate the environmental disturbances from wind, waves, and currents.

2. Design and develop disturbance compensating control method to improve the reliability of USVs against potential environmental disturbances. This method should improve the overall performance of the USV system in the presence/absence of environmental disturbances.

3. Design and develop online model-based fault detection and diagnosis (FDD) techniques [23], which can not only set up a cost-effective monitoring framework, but also be used for integration with fault tolerant control (FTC) techniques [23] in active fault-tolerant architectures.

4. Design and develop FTC strategies to improve the reliability and availability of USVs against potential actuator faults. Preferably, these FTC strategies should not only provide fault tolerance capabilities to USVs, but also improve the overall performance of the system under both fault-free and faulty conditions.

5. Besides the above-mentioned issues, model uncertainties and actuator saturation should also be explicitly studied.

The proposed research in brief is expected to synthesize advanced levels of guidance, navigation, and control capabilities in USVs, which in turn can guarantee the reliable and satisfactory performance of USVs at both individual and multiple USVs levels. The schemes and strategies expected from this research proposal will be verified by a series of simulations on both a well-known USV benchmark and real USVs in the presence of environmental disturbances, model uncertainties, actuator saturation, and different realistic fault scenarios.

4 Research Methodologies

4.1 USV Model

Dynamics play a significant role in the motion analysis and control of USVs. The most widely adopted dynamic model [19, 20] by the USV control community is:

$$M\dot{\nu} + D(\nu)\nu = \tau, \tag{1}$$

where $M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{32} & m_{33} \end{bmatrix}$, $D(\nu) = \begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix}$, $\nu = [u \ v \ r]^T$, and $\tau = [\tau_u \ \tau_v \ \tau_r]^T$. $m_{11} = m - X_{\dot{u}}$, $m_{22} = m - Y_{\dot{\nu}}$, $m_{33} = I_z - N_{\dot{r}}$, $m_{23} = m\chi_g - Y_{\dot{r}}$, and $m_{32} = m\chi_g - N_{\dot{v}}$. $d_{11} = -X_u - X_{u|u|}|u|$, $d_{22} = -Y_v$, $d_{33} = -N_r + (m\chi_g - \frac{1}{2}N_{\dot{v}} - \frac{1}{2}Y_{\dot{r}})u$, $d_{23} = -Y_r + (m - X_{\dot{u}})u$, and $d_{32} = -N_v + (X_{\dot{u}} - Y_{\dot{v}})u$. The terms m_{11}, m_{22}, m_{23}, m_{32}, and m_{33} represent the USV inertia, while d_{11}, d_{22}, d_{23}, d_{32}, and d_{33} represent the hydrodynamic damping forces.

Assuming the fore/aft symmetry, the non-diagonal terms in M and $D(\nu)$ can be eliminated, it is also reasonable to neglect the sway velocity (this derives $v = 0$) since it is much smaller than the surge velocity in the case of underactuated USV. The following simplified USV model consisting of surge and steering dynamics can then be achieved:

$$\begin{aligned} \dot{u} &= A_u + B_u\tau_u \\ \dot{\psi} &= r \\ \dot{r} &= A_r r + B_r\theta, \end{aligned} \tag{2}$$

where ψ, θ, and τ_u denote yaw angle, rudder deflection, and propulsion force, respectively. $A_u = -d_{11}/m_{11}$, $A_r = -d_{33}/m_{33}$, $B_u = 1/m_{11}$, $B_r = N_\theta/m_{33}$.

Based on model (2), a linear time-invariant model and a linear parameter varying (LPV) model can be obtained, respectively.

1. Assuming the surge speed is time-invariant, a linear time-invariant model can be obtained:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t), \end{cases} \tag{3}$$

where $u(t) = [\tau_u \ \theta]^T \in \Re^m$, $x(t) = [u \ \psi \ r]^T \in \Re^n$, and $y(t) \in \Re^p$ represent the system's control input, state, and output matrix, respectively. $A = \begin{bmatrix} A_u & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & A_r \end{bmatrix}$, $B = \begin{bmatrix} B_u & 0 \\ 0 & 0 \\ 0 & B_r \end{bmatrix}$, and $C = diag[1 \ 1 \ 1]$ are time-invariant.

2. Assuming the surge speed is time-varying, a LPV model can then be obtained:

$$\begin{cases} \dot{x}(t) = A(\rho)x(t) + B(\rho)u(t) \\ y(t) = C(\rho)x(t), \end{cases} \tag{4}$$

where $A(\rho) = \begin{bmatrix} A_u & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & A_r \end{bmatrix}$, $B(\rho) = \begin{bmatrix} B_u & 0 \\ 0 & 0 \\ 0 & B_r \end{bmatrix}$, and $C(\rho) = diag[1\ 1\ 1]$. Additionally, ρ is a time-varying vector of real parameters that contains all possible trajectories of the system.

4.2 Active Disturbance Estimation and Compensating Control

As illustrated in Fig. 5, the system comprises a normal controller, a disturbance estimator, and a disturbance compensator. Before encountering the environmental disturbance, the USV is controlled by normal controller to achieve the optimized control performance. Once the disturbance occurs, the estimator detects the disturbance, and estimates its amplitude according to an adaptive law. Based on the estimated value, the compensator generates an appropriate control input $u_{ad}(t)$ in combination with the nominal control input $u(t)$. Eventually, the proposed active disturbance compensating controller is capable of rejecting environmental disturbances.

The ultimate control input can also be written in the following mathematical representation:

$$u_c(t) = u(t) + u_{ad}(t), \tag{5}$$

where $u_c(t)$ denotes the ultimate control input, the additional control input $u_{ad}(t) = 0$ when USV works in calm water, and deviates from this equilibrium point in the event of external disturbances.

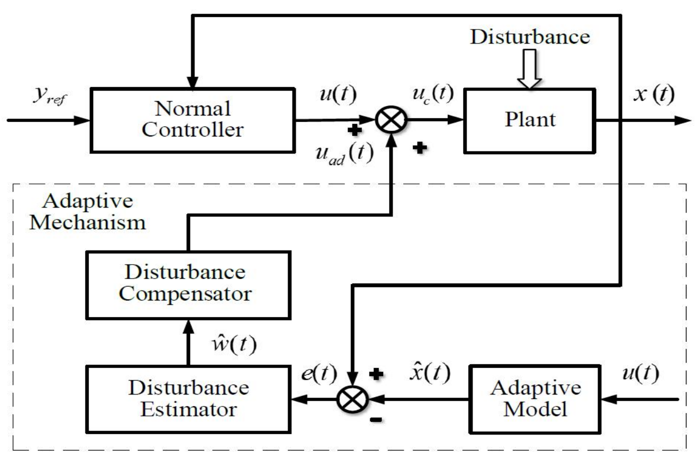


Figure 5: Schematic diagram of the proposed active disturbance compensating control approach.

4.2.1 Environmental Disturbances

Waves and currents are regarded as the dominant factors of influencing marine surface vehicle performance [20].

1. *Waves*: the wave model can be described as:

$$w(s) = \frac{K_\omega s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} h(s), \tag{6}$$

where $h(s)$, ω_0, ζ, and K_ω are white noise, model frequency, damping coefficient, and constant, respectively.

2. *Currents*: the two-dimensional current model is composed by the direction of the current γ_c and the average speed of current $V_c(t)$. Therefore, the body-fixed kinematic equations can be expressed as:

$$\begin{aligned} u_c &= V_c(t)cos(\gamma_c - \psi) \\ v_c &= V_c(t)sin(\gamma_c - \psi), \end{aligned} \tag{7}$$

where u_c and v_c denote the currents velocity along the directions of surge and sway, respectively, ψ denotes the yaw angle of USV.

4.2.2 Online Disturbance Estimation

In order to effectively obtain the disturbances on-line, an adaptive observer is constructed as:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + G\hat{w}(t) + L(\hat{x}(t) - x(t)), \tag{8}$$

where $\hat{x}(t)$ and $\hat{w}(t)$ denote the estimated values of the state and external disturbances, respectively. L represents the observer gain matrix, which is selected to make $A_L = (A + L)$ Hurwitz.

The derivative of the state error $e(t) = \hat{x}(t) - x(t)$ is:

$$\dot{e}(t) = A_L e + G\tilde{w}(t), \tag{9}$$

where $\tilde{w}(t) = \hat{w}(t) - w(t)$ is the estimation of disturbance error and $\tilde{w}(t) = diag[\tilde{w}_1(t)...\tilde{w}_n(t)]$.

Consequently, the estimation of disturbance can be obtained by:

$$\hat{w}_c(t) = \hat{w}(t) - L_0(t)e(t), \tag{10}$$

where $\hat{w}(t)$ is determined by the following adaptive estimation law:

$$\begin{aligned} \dot{\hat{w}}(t) &= Proj_{[\underline{w},\overline{w}]}\{-kG^T Pe(t)\} \\ &= \begin{cases} 0 & \text{if } \hat{w}_a(t) = \underline{w}, -kG^T Pe(t) \leqslant 0 \\ & \text{or } \hat{w}_a(t) = \overline{w}, -kG^T Pe(t) \geqslant 0, \\ -kG^T Pe(t) & \text{otherwise,} \end{cases} \end{aligned} \tag{11}$$

and P is calculated by:

$$\begin{aligned} &PA_L + A_L^T P = -Q, \\ &G^T P = H, \end{aligned} \tag{12}$$

where $k > 0$ denotes the adaptive law gain, $Proj\{\cdot\}$ is for projecting the estimates $\hat{w}(t)$ to the acceptable disturbance interval $[\underline{w}, \overline{w}]$. The symmetric positive definite matrices P, $Q \in \Re^{(l+n+2m)\times(l+n+2m)}$, and matrix $H \in \Re^{r\times(l+n+2m)}$. $L_0(t)$ specifies the correction gain.

4.2.3 Disturbance Compensating Strategies

The closed-loop state feedback control law in combination with the integral tracking action [24] can be given by:

$$u(t) = K_{st}x_a(t) = K_\varepsilon \int_0^t \varepsilon(t)dt + K_x x(t), \tag{13}$$

where $K_{st} = [K_\varepsilon, K_x] \in \Re^{m\times(l+n)}$. The state feedback control law can be designed according to linear quadratic regulator (LQR). The corresponding closed-loop augmented system in state feedback case can therein be written as:

$$\begin{cases} \dot{x}_a(t) = A_{st}x_a(t) + G_a y_r(t) \\ y_a(t) = C_a x_a(t), \end{cases} \tag{14}$$

where $A_{st} = A_a + B_a K_{st}$.

The disturbance compensating input $u_{ad}(t)$ can then be calculated, solving the following optimization problem:

$$\min_{u_{ad}(t)\in\Re^n} ||B_a u_{ad}(t) + G_a \hat{w}_c(t)|| \tag{15}$$

subject to

$$SB_a u_{ad}(t) \leq -SA_a e(t) - H_w, \tag{16}$$

$$Eu_{ad}(t) \leq T - Eu(t), \tag{17}$$

where state constraints are defined by S and F, and control input constraints are represented by matrices E and T, $H_w = max(SG_a\hat{w}_c(t))$.

Consequently, the ultimate control input can be achieved:

$$u_c(t) = u(t) + u_{ad}(t) = K_{st}x_a(t) + u_{ad}(t). \tag{18}$$

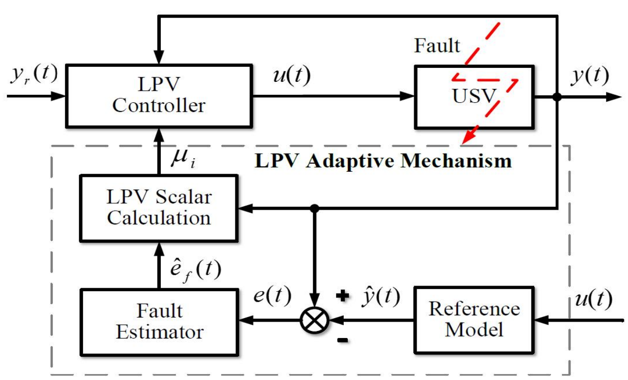


Figure 6: Schematic diagram of the proposed LPV control approach.

4.3 Active Fault Detection, Diagnosis and Tolerant Control

In this subsection, both FDD and FTC approaches are presented. As outlined in Fig. 6, its overall control design structure can also be described as follows: 1) a LPV adaptive observer is constructed to estimate the USV state; 2) the magnitude of parameter variation can then be obtained according to the errors between USV outputs and an adaptive reference model outputs; 3) based on estimated parameters, a LPV scalar calculation scheme is adopted to get the LPV scalar, using the *bounding box approach* [25]; 4) finally, a LPV controller is synthesized with this scalar.

4.3.1 USV Linear Parameter Varying Model

The USV LPV model (4) can be expressed as:

$$(A(\rho), B(\rho), C(\rho)) = \sum_{i=1}^{N} \mu_i (A_i, B_i, C_i) \in Co\{(A_i, B_i, C_i) : i = 1, ..., N\} \tag{19}$$

with the convex coordinates $\mu_i > 0$ and $\sum_{i=1}^{N} \mu_i = 1$, $(A_i, B_i, C_i)(i = 1, ..., N)$ are unknown constant matrices that denote USV models at all vertices, and $Co\{\cdot\}$ represents the convex hull.

$$\Omega = \{\mu_i \in \Re^N, \mu_i \geq 0, \sum_{i=1}^{N} \mu_i = 1\}, \tag{20}$$

where Ω denotes a convex set, μ_i denotes the function of time-varying parameter ρ, and the rule of its selection can use the *bounding box approach* presented in [25]. Therefore, a LPV system can be constructed under the condition that the parameter dependence is affine, that is the matrices $A(\rho)$, $B(\rho)$, and $C(\rho)$ affinely depend on ρ, while ρ varies over a fixed polytope.

4.3.2 Modeling of Rudder Faults

As the conjunction between control command and physical action on a USV, actuator plays an essential role in USV control system. However, each actuator of USV subjects to fault due to numerous effects, such as wear and tear of the steering gear, mechanical deformation, and fatigue damage. When the rudder failed to conduct the expected control commands, the stability and performance of system cannot be ensured.

Although various actuator faults exist in practice, the loss of effectiveness is considered here. Thus, the effectiveness of m actuators can be represented as:

$$u_f(t) = L_f u(t) \tag{21}$$

where $u_f(t) = [u_{f1}(t), ..., u_{fm}(t)]^T$, $u(t) = [u_1(t), ..., u_m(t)]^T$, and $L_f = diag\{l_{f1}, ..., l_{fm}\}$ denote the desired control command, the actual actuator actions, and the effectiveness factors, respectively. Meanwhile, $u_{fi}(t)$ is the control command in the event of ith actuator fault, $0 \leq l_{fi} \leq 1$ denotes the partial loss of effectiveness of ith actuator. $l_{fi} = 1$ represents a healthy actuator, while $l_{fi} = 0$ means a complete actuator failure.

The system (4) with actuator faults can thereby be formulated as:

$$\begin{cases} \dot{x}(t) = A(\delta)x(t) + B(\delta)L_f u(t) = \sum_{i=1}^{N} \mu_i [A_i x(t) + B_i L_{fi}(t)u(t)] \\ y(t) = Cx(t), \end{cases} \tag{22}$$

it is noteworthy that the effectiveness factor appears linearly in the LPV model.

4.3.3 Online Fault Detection and Diagnosis

To estimate the effectiveness of faulty actuators, the following adaptive reference model is constructed:

$$\begin{cases} \dot{\hat{x}}(t) = A(\rho)\hat{x}(t) + B\hat{L}_f(t)u(t) = \sum_{i=1}^{N} \mu_i[A_i\hat{x}(t) + B\hat{L}_{fi}(t)u(t)] \\ \hat{y}(t) = C\hat{x}(t), \end{cases} \tag{23}$$

Thus, the error between (22) and (23) can be denoted as:

$$\dot{e}_x(t) = \sum_{i=1}^{N} \mu_i A_i e_x(t) + Be_{fi}(t)u(t), \tag{24}$$

where $e_x(t) = \hat{x}(t) - x(t)$, $e_f(t) = \sum_{i=1}^{N} \mu_i(e_{fi}(t))$, and $e_{fi}(t) = \hat{L}_{fi}(t) - L_{fi}(t)$.

For the convenience of constructing an adaptive law for the parameter (actuator efficiency factor) estimation, (24) can be rewritten as:

$$\dot{e}_x(t) = \sum_{i=1}^{N} \mu_i[A_i e_x(t) + B\tilde{u}_f(t)], \tag{25}$$

where $\tilde{u}_f(t) = \sum_{i=1}^{N} \mu_i[\hat{L}_{fi}(t)u(t) - L_{fi}(t)u(t)] = \hat{u}_f(t) - u_f(t)$.

Consequently, the effectiveness of actuators can be obtained by the following adaptive law:

$$\dot{\hat{u}}_f(t) = -\Gamma \sum_{i=1}^{N} \mu_i[B^T P_i e_x(t) + R(t)], \tag{26}$$

where $R(t)$ includes a sliding mode term is to guarantee the fast parameter convergence [26].

4.3.4 Fault Tolerant Control Strategies

Consider the closed-loop system model (14). For a given positive scalar γ, there exists positive symmetric matrices $X \in \Re^{(n+l)\times(n+l)}$, $Z(\rho) = \sum_{i=1}^{N} \mu_i Z_i \in \Re^{(n+l)\times(n+l)}$, and $Y(\rho) = \sum_{i=1}^{N} \mu_i Y_i \in \Re^{m\times(n+l)}$ making inequalities (28) and (29) hold, where the symbol $*$ denotes a symmetric entry. Moreover, the following performance index can be minimized:

$$J \leqslant \gamma \int_0^t y_r^T(t) y_r(t) dt + x^T(t) Z^{-1}(\rho) x(t). \tag{27}$$

Assuming that the LPV system (4) can be approximated by an affine LPV model [27]. The infinite sets of LMIs of (28) and (29) can then be reduced to finite number of calculation in each vertex. Therefore, it is only needed to make (28) and (29) hold in each vertex, while the stability of closed-loop system (14) can be guaranteed under the supervision of state feedback control law $u(t) = K(\rho)x_a(t)$ with the offline computed vertex controllers $K = Y_i X^{-1}$. Ultimately, the LPV state feedback control law can be obtained as $K(\rho) = \sum_{i=1}^{N} \mu_i Y_i X^{-1}$.

5 Timeline

The following table outlines the progress for accomplishing the objectives of the PhD study.

$$
\begin{bmatrix} A(\rho)X + B(\rho)Y(\rho) + (A(\rho)X + B(\rho)Y(\rho))^T & G(\rho) & Y^T(\rho)R^{1/2} & XQ^{1/2} \\ * & -\gamma I & 0 & 0 \\ * & * & -I & 0 \\ * & * & * & -I \end{bmatrix} < 0, \tag{28}
$$

$$
\begin{bmatrix} Z(\rho) & I \\ I & X \end{bmatrix} > 0. \tag{29}
$$

Table 4: Timelines for PhD study

Main Tasks	**2012-2013**			**2013-2014**			**2014-2015**			**2015-2016**			**2016-2017**		
	S	**F**	**W**	**S**	**F**	**W**	**S**	**F**	**W**	**S**	**F**	**W**	**S**	**F**	**W**
Course Study	-	>	>											-	-
Literature Review	-	>	>	>	>									-	-
Comprehensive Examination	-				>									-	-
USV Control: Disturbance Estimation	-				>	>								-	-
USV Control: Disturbance Compensation	-					>	>							-	-
USV FDD & FTC: Actuator Faults	-							>	>	>				-	-
USV Control Allocation	-								>	>	>			-	-
USV Regulation-based Collision Avoidance	-								>	>	>			-	-
USVs Cooperative Control	-									>	>	>		-	-
USVs Experimental Setup and Validation	-									>	>	>		-	-
Publications	-				>	>	>	>	>	>	>	>	>	-	-
Thesis Writing	-											>	>	-	-

Note: **S**: summer; **F**: fall; **W**: winter semesters; FDD: fault detection and diagnosis; FTC: fault tolerant control; $>$: available; $-$: not available.

6 Anticipated Significance of the Work and Future Work

6.1 Conclusion

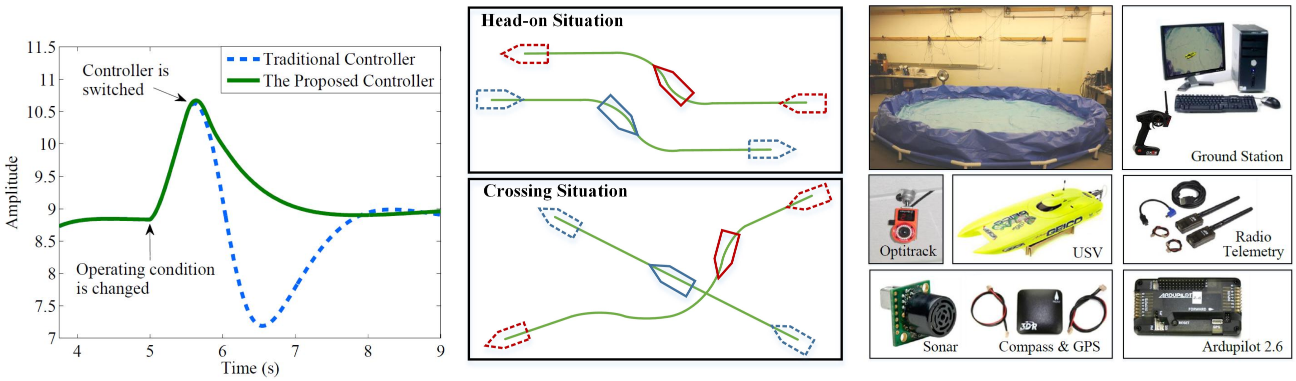
Although tremendous efforts on USVs GNC have been dedicated to make USVs more autonomous, there still exist significant challenges in the development of USVs. Many key technical issues must be solved to bring the autonomy up to a state required for more sophisticated and hazardous applications. In the near future, the development of fully autonomous USVs in the dynamic maritime environment remains an open issue, and there are numerous ongoing work on this topic.

The results of the research proposed here will be disseminated in the form of conferences, journals, and technical reports. Some preliminary work of the proposed research in particular disturbance estimation and compensating, FDD and FTC at individual USV level are completed, and partial results are also published. Up to now, all my previous research are summarized in several journal papers [28–32] and conference papers [33–41].

6.2 Future Work

1. *Adverse transient behavior attenuation* (Fig. 7(a)): In practical control of nonlinear systems, several linear controllers are often used. This phenomenon may cause undesired transient behaviors due to possible large and sudden variations of the control signal (such as FTC and disturbance compensating control). The adverse behavior can degrade the system performance, even destabilize the closed-loop system. The effort to attenuate this adverse effect

will be studied in the next stage research;



(a) (b) (c)

Figure 7: Simple examples of (a) adverse transient behavior attenuation, (b) regulation-based collision avoidance, and (c) experimental platform.

2. *Regulation-based collision avoidance* (Fig. 7(b)): Collision avoidance is critical for the safety of USVs and objectives in the vicinity, it is in particular significant when high speed USVs moving in the narrow/busy waters. Besides this, manned vessels are required to operate obeying a specific marine traffic regulation. Thus, designing an effective collision avoidance in combination of this regulation will also be investigated in my next stage research;

3. *Fault tolerant cooperative control*: Cooperative control of a group of USVs can bring tremendous benefits to desired missions such as higher efficiency, wider operational ranges, and enhanced capabilities. In addition, each USV may encounter actuator fault and collision, which can potentially affect both itself and its surrounding objects. Therefore, the development of an effective cooperative control (leader-follower formation control) scheme in combination with fault tolerant and collision avoidance capabilities will be further studied;

4. *Control allocation*: Proper control allocation is of significance for USVs maneuvering, which can contribute to numerous benefits, such as less fuel consumption due to frequently operating rudders other than operating propulsion, enhanced disturbance compensating and FTC capabilities. Additionally, current effort is mainly dedicated to time-invariant system. Control allocation on time-varying (linear parameter varying) USV systems to apply for FTC of USVs will also be investigated;

5. *Experimental validation*: In order to verify the effectiveness of the proposed methodologies (FTC, disturbance compensating control, and cooperative control of USVs) in the practice, a USV platform (see Fig. 7(c)) is to be developed and several outdoor experiments will also be carried out.

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7 Appendix: Progress to Date

With respect to the presented timeline (Table 4) in Section 5, this section provides a brief review of the progress to date of the PhD thesis work. The aforementioned disturbance estimation and compensating approaches, and FDD and FTC strategies against actuator faults are validated in a USV benchmark, respectively. Simulations are conducted in the presence of disturbances, actuator constraints, and actuator failures, respectively.

7.1 Disturbance Estimation and Compensating

The considered external disturbances here are so significant on the effect to the behavior of USV system, effective disturbance estimation and compensating control strategies are therefore needed for guaranteeing the stability and desired performance of the USV system. Table 5 presents the considered disturbances in the simulation.

Table 5: Illustration of considered disturbances in the simulation

Disturbance	**Representation**	**Time Period (sec)**
Constant Disturbance	$-0.4\ m/s^2$	$60-140$
Constant Disturbance	$-0.5\ m/s^2$	$60-140$
Sinusoidal Disturbance	$0.4sin(0.1t)\ m/s^2$	$60-200$

Five controllers are compared in the simulation, which are listed in Table 6. The rudder deflection bound is set to be $[-35\ deg,\ 35\ deg]$, the maximum rudder speed is constrained within $[-20\ deg/s,\ 20\ deg/s]$. To avoid abrupt turns, the yaw rate is limited in $[-20\ deg/s,\ 20\ deg/s]$.

Table 6: Illustration of controllers that are compared in the simulation

Name	**Illustration**
Controller-1	Normal controller with consideration of actuator and state constraints.
Controller-2	TI-ADCTC with consideration of actuator and state constraints.
Controller-3	TV-ADCTC is the proposed controller considering actuator and state constraints.
Controller-4	TV-ADCTC without consideration of actuator and state constraints.
Controller-5	Normal controller without consideration of actuator and state constraints.

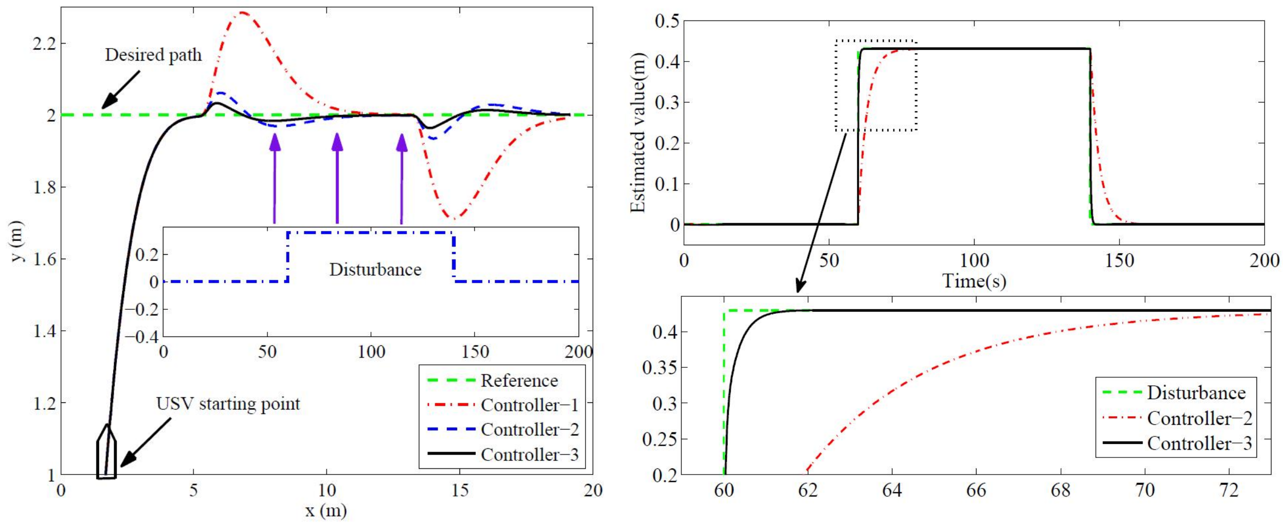
Note: Normal controller is LQR controller; TI-ADCTC is time-invariant active disturbance compensating tracking controller; TV-ADCTC is time-varying active disturbance compensating tracking controller.

7.1.1 Constant Disturbance Estimation and Compensating

The path following performance of the selected three control schemes is illustrated in Fig. 8(a). The performance achieved by the proposed Controller-3 is significantly superior than that of the Controller-1 and Controller-2 in the presence of environmental disturbance. From Fig. 8(b), asymptotic convergence of disturbance estimation error can be achieved using either Controller-2 or Controller-3, while Controller-3 converges faster than Controller-2.

More specifically, the performance of three controllers are all shown in Table. 7. It is worthy to mention that the deviation can be gradually reduced because of the integral action of the tracking error.

In addition, in order to verify the effectiveness of control schemes under actuator and state constraints, a larger constant disturbance ($-0.5\ m/s^2$) is also imposed into system. As illustrated in Fig. 9(a), about 0.04 m of maximal cross-track error is yielded by Controller-3 during the



(a) (b)

Figure 8: (a) Path following and (b) disturbance estimation performance under different control schemes.

Table 7: Performance comparison of different controllers under constant disturbance

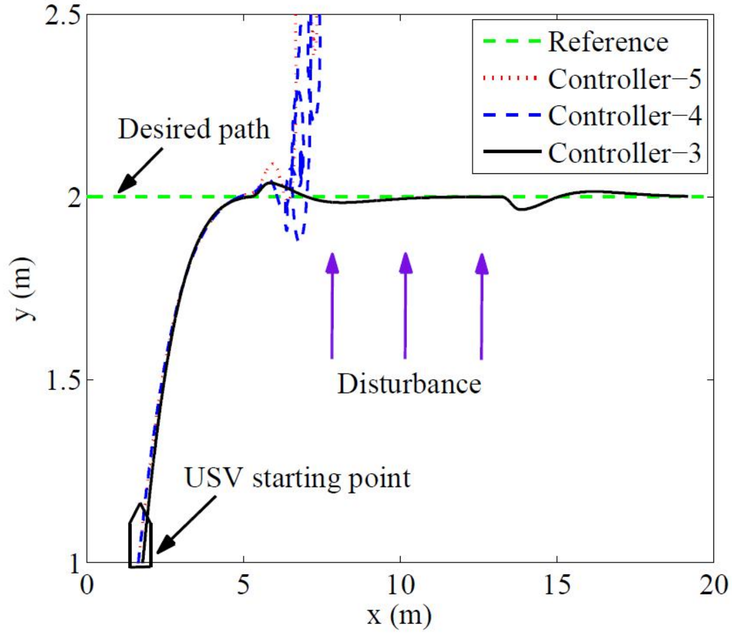
	Controller-1	**Controller-2**	**Controller-3**
Maximal cross-track error	0.28 m	0.065 m	0.03 m
Maximal heading error	23 deg	10 deg	7 deg
Maximal yaw rate	7.8 deg/s	5.2 deg/s	4 deg/s
Maximal rudder deflection	-30.5 deg	-30 deg	-29.5 deg
Maximal rudder rate	12 deg/s	15 deg/s	20 deg/s

disturbance. However, the USV that is controlled by either Controller-4 or Controller-5 cannot track the desired path. Fig. 10(a) and Fig. 10(b)) shows that nearly $8/deg$ of maximal heading error is generated by Controller-3. Meanwhile, yaw rate constraints are violated by both Controller-4 and Controller-5. From Fig. 9(b) and Fig. 9(c)), rudder deflection and rate are oscillatory in the case of Controller-4 and Controller-5. By contrast, Controller-3 drives the rudder more smoothly. When the disturbance occurs, Controller-3 can still perform under actuator saturation, whereas the actuators under the other two controllers are saturated. Therefore, Controller-3 enables the rudder to react more gently than the other two controllers. This is of significant importance in practice because the extreme utilization of rudder is the main cause of wearing down its working lifetime. Moreover, over-quick turning may increase the possibility of capsizing.

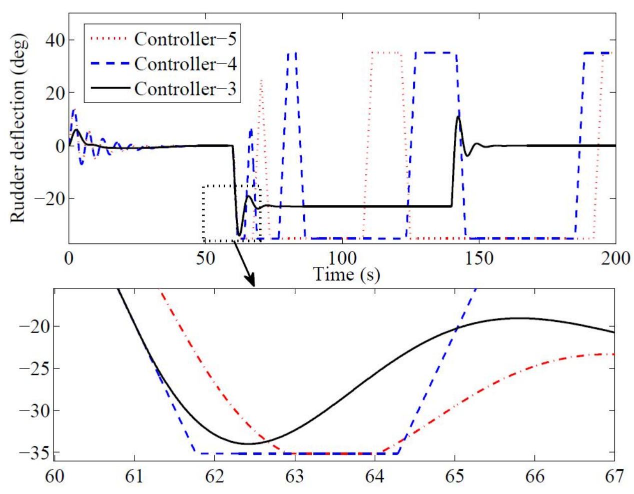
7.1.2 Time-varying Disturbance Estimation and Compensating

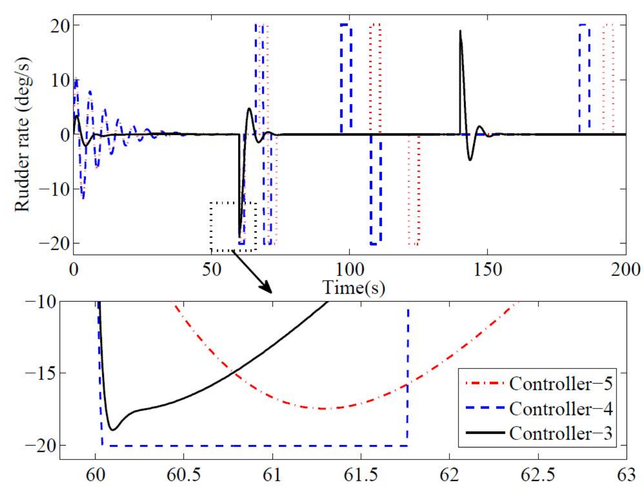
In this scenario, performance of the compared controllers are demonstrated in Fig. 11(a). With respect to path following, faster convergence and less oscillation are obtained by Controller-3 rather than other two controllers. Additionally, from Fig. 11(b), the disturbance can be estimated by either Controller-2 or Controller-3. Whereas, it is evident that the proposed control scheme can remarkably improve the disturbance estimation speed.

As can be observed in Table 8, Controller-3 has a slight overshoot in both cross-track and heading errors (0.05 m and 6 deg) in the presence of disturbance. However, about 0.3 m of



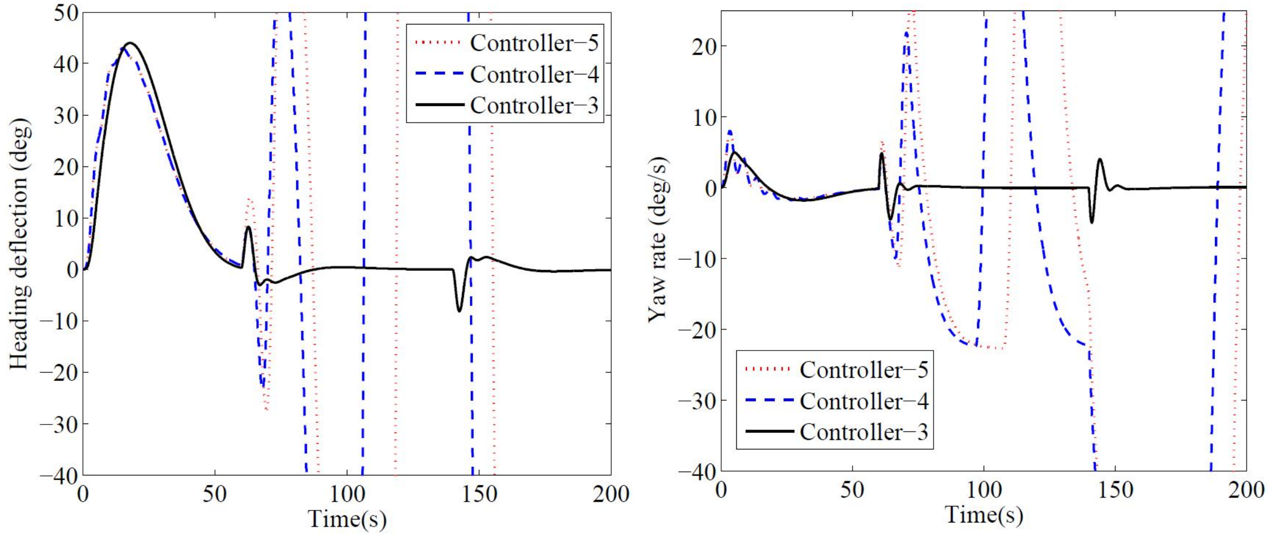
(a)





(b) (c)

Figure 9: (a) Path following, (b) rudder deflection, and (c) rudder rate performance under different control schemes.



(a) (b)

Figure 10: The responses of (a) heading deflection and (b) yaw rate under different control schemes.

Table 8: Performance comparison of different control schemes under sinusoidal disturbance

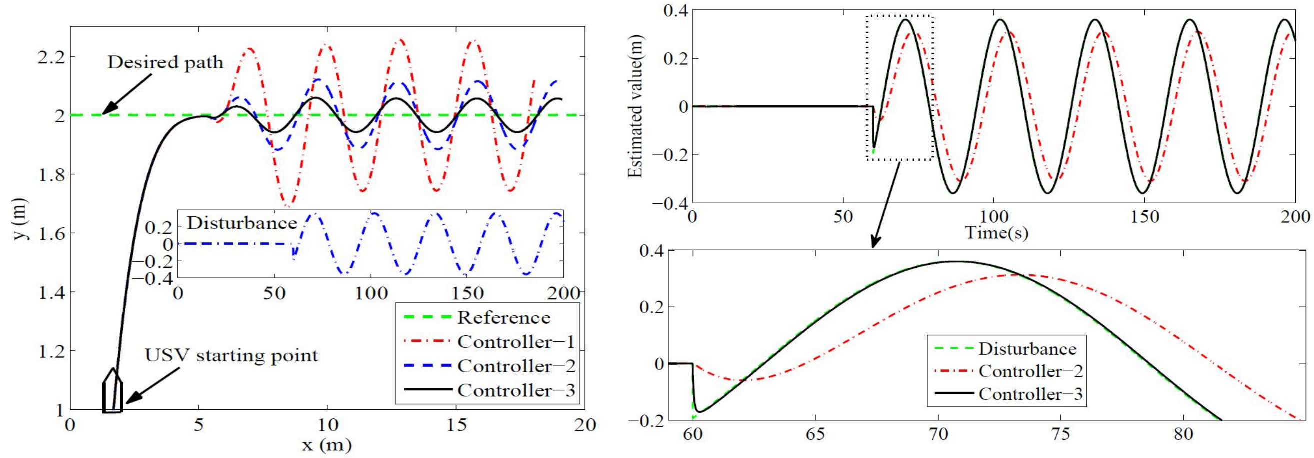
	Controller-1	**Controller-2**	**Controller-3**
Maximal cross-track error	0.3 m	0.12 m	0.05 m
Maximal heading error	35 deg	15 deg	6 deg
Maximal yaw rate	6.5 deg/s	3.5 deg/s	2.5 deg/s
Maximal rudder deflection	24 deg	22 deg	21 deg
Maximal rudder rate	4.8 deg/s	6.7 deg/s	9.9 deg/s

cross-track error and 35 deg heading error are produced when Controller-1 is commissioned, and around 0.12 m of cross-track error and 15 deg heading error are generated under the supervision of Controller-2.

7.2 FTC of USV under Varying Surge Speed and Actuator Faults

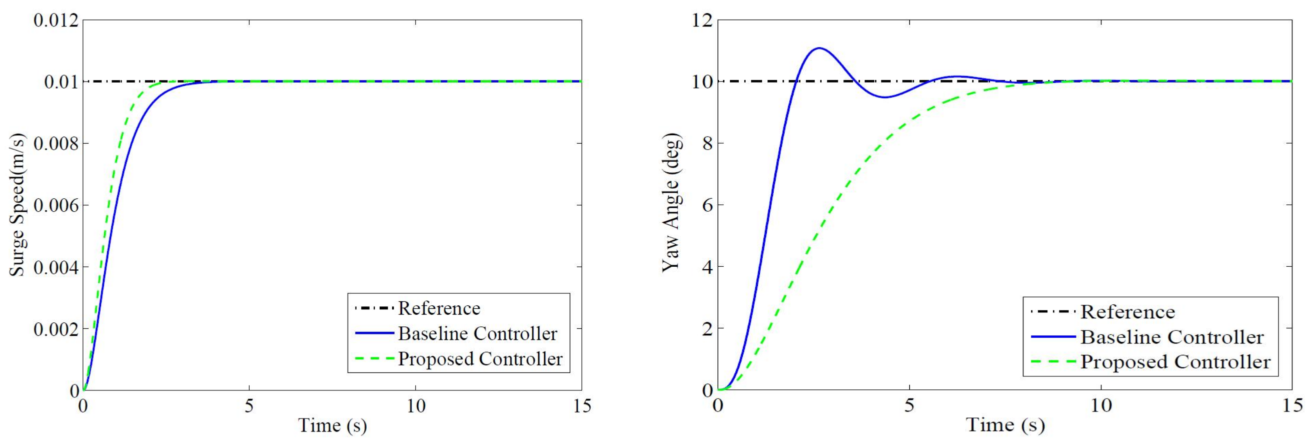
In this example, a conventional linear quadratic regulator (LQR) controller is selected as the baseline controller to compare with the proposed LPV controller in the presence of both surge speed variation and actuator fault (loss of effectiveness). The variation ranges of surge speed and actuator fault are limited within $[0.01\ m/s,\ 0.1\ m/s]$ and $[0,\ 70\%]$, respectively. The propulsion force and rudder moment are constrained in $[-2\ N,\ 2\ N]$ and $[-1.5\ Nm,\ 1.5\ Nm]$, respectively. Moreover, in this scenario, the surge speed is changed from 0.1 m/s to 0.01 m/s and the actuator fault is selected as loss of 60% effectiveness. The compared controller is tuned with 0.1 m/s surge speed and without actuator fault.

As shown in Fig. 12(a) and Fig. 12(b), the performance of surge speed and yaw angle control are significantly improved by the proposed controller in comparison of the baseline controller. The superior performance of the proposed LPV controller is attribute to its gain-scheduling feature. In addition, Fig. 13(a) and Fig. 13(b) illustrate either propeller or rudder is under saturation.



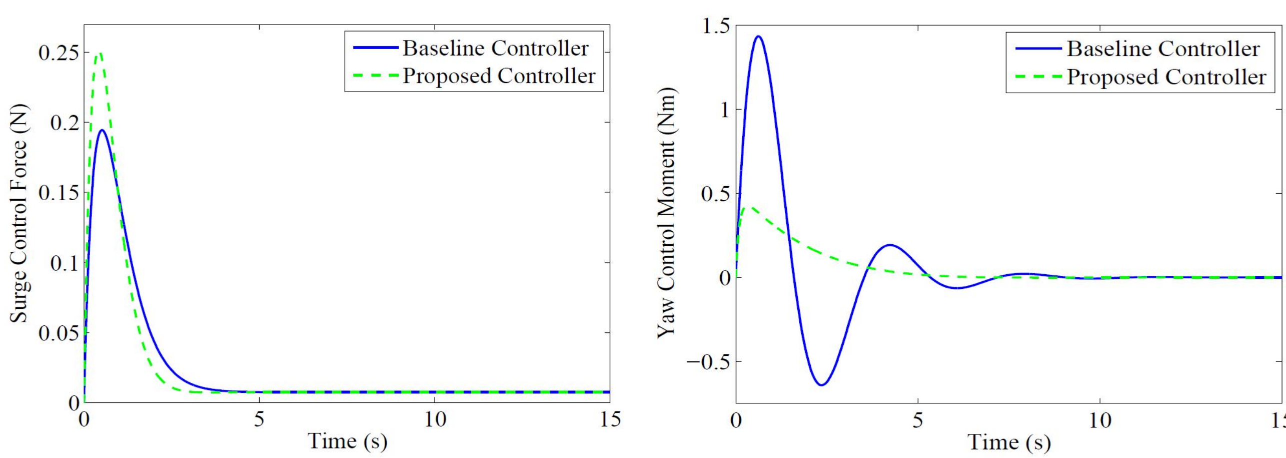
(a) (b)

Figure 11: (a) Path following and (b) Sinusoidal disturbance estimation performance under different control schemes.



(a) (b)

Figure 12: Performance of (a) surge speed and (b) yaw angle.



(a) (b)

Figure 13: Performance of (a) propeller and (b) rudder.