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Preface

Networked Control Systems (NCSs) are spatially distributed systems in which the communication between sensors, controllers, and actuators occurs through shared band-limited communication networks. The flexibility in communication architectures, low cost in installation and maintenance, and high reliability make NCSs the future of industrial control systems. Network-based control systems have found a wide range of applications in areas including aircrafts, autonomous vehicles, transportation systems, Unmanned Marine Vehicles (UMVs), and power systems.

The development of UMVs is particularly significant in providing cost-effective solutions to coastal and offshore problems. UMVs are widely used in monitoring, oil and pollution clean-up, scientific characterization, exploration, and military operations such as mine sweeping and border surveillance. It should be mentioned that control for a UMV is usually based on a remote land-based or mother ship-based control station in network environments. The UMV's states such as yaw velocity, roll angle, and heading angle are sampled and transmitted to the control station through the sampler-to-control station communication network channel, while control instructions are constructed and transmitted to the steering machine through the control station-to-actuator communication network channel.

Note that the insertion of communication networks into control systems will inevitably induce network delays and packet dropouts. On the other hand, the occurrence of sensor faults and/or actuator faults in NCSs and UMVs is usually unavoidable. Considering the wide range of applications of NCSs, it is of paramount importance to investigate the stability analysis, stabilization, and fault detection for NCSs. Moreover, how to propose appropriate motion control and fault detection schemes for UMVs in network environments is attractive and practically valuable.

This monograph first presents systematic results for stability analysis, stabilization, and fault detection of NCSs. Then, within the framework of networked control, the problems of heading control, Fault Detection Filter (FDF) and controller coordinated design, dynamic positioning, and cooperative target tracking of UMVs are investigated in detail. Some fundamental concepts of stability analysis, stabilization, motion control, and fault detection are presented with insight and understanding.

Some benchmark examples are provided to show the merits and effectiveness of the network-based UMVs control schemes.

Structure and readership. This monograph is concerned with networked control and its applications in motion control and fault detection of UMVs. In Chap. 1, the importance of studying NCSs and network-based UMVs is first analyzed. Then the corresponding research developments and motivations are provided. Moreover, issues in stability analysis and stabilization of NCSs, and motion control and fault detection of UMVs are presented.

Stabilization and fault detection of NCSs: In Chap. 2, stability analysis and stabilization for an NCS under simultaneous consideration of non-uniformly distributed packet dropouts and interval time-varying sampling periods are investigated. Chapter 3 addresses observer-based FDF design for a continuous-time NCS by taking packet dropouts and network-induced delays into account. In Chap. 4, the output feedback controller design problem for NCSs under an independent and identically distributed (IID) scheduling protocol is discussed. Based on a stochastic impulsive delayed model, sufficient conditions for guaranteeing the stability of the studied system in the mean-square sense are achieved.

Motion control and fault detection of UMVs: In Chaps. 5–9, the problems of heading control, fault detection, dynamic positioning, dynamic output feedback (DOF) control, and cooperative target tracking for UMVs are investigated. In Chap. 5, a novel network-based model for a UMV is established by constructing a heading control error system and purposely dropping some control input packets. Then network-based heading control and rudder oscillation reduction are addressed. Chapter 6 deals with the network-based modeling, and observer-based FDF and controller coordinated design for a UMV. Chapter 7 investigates Takagi-Sugeno (T-S) fuzzy dynamic positioning controller design for a UMV in network environments. In Chap. 8, network-based models for a UMV subject to network-induced characteristics are established. Based on these models, dynamic output feedback controllers (DOFCs) are designed to attenuate the oscillation amplitudes of the yaw velocity error and the yaw angle. Chapter 9 deals with the cooperative target tracking problem of multiple UMVs under switching interaction topologies.

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Contents

Acronyms

$\mathbb{R}^n$	Set of n-dimensional real vectors
$\mathbb{R}^{n \times m}$	Set of all $n \times m$ real matrices
A^{-1}	Inverse of an invertible matrix A
A^T	Transpose of a matrix A
$A \geq 0$	Matrix A is symmetric positive semi-definite
$A > 0$	Matrix A is symmetric positive definite
$A \leq 0$	Matrix A is symmetric negative semi-definite
$A < 0$	Matrix A is symmetric negative definite
$\lambda_{\max}(A)$	The maximum eigenvalue of a real symmetric matrix A
$\lambda_{\min}(A)$	The minimum eigenvalue of a real symmetric matrix A
$\|x\|$	2-norm of a real vector x
$\mathrm{diag}\{\cdots\}$	Block-diagonal matrix
$\mathrm{tr}(A)$	Trace of a matrix A
$\mathrm{Ones}(m, n)$	m-by-n matrix with all entries equal to 1
$\mathrm{Prob}\{\cdot\}$	Probability distribution
$E\{\cdot\}$	The expectation operation
I	Identity matrix with appropriate dimensions
0	Zero matrix with appropriate dimensions
I_m	$m \times m$ identity matrix
*	Entries of a matrix implied by symmetry
Sup	Supremum

Chapter 1
Introduction

In this chapter, we first introduce some underlying concepts of network-based control and motion control of unmanned marine vehicles (UMVs). Then we briefly review research motivations on scheduling protocol design and fault detection filter (FDF) design for networked control systems (NCSs). Moreover, we review how network-based heading control, fault detection, dynamic positioning, dynamic output feedback control, and cooperative target tracking for UMVs are motivated and promoted in the control community. Afterwards, we summarize future research topics. Finally, we give a brief outline of the monograph.

1.1 Stability and Stabilization of NCSs

NCSs are spatially distributed systems in which the communication between sensors, controllers and actuators occurs through shared band-limited communication networks [1–3]. Figure 1.1 depicts the typical structure for NCSs. The flexibility in communication architectures, low cost in installation and maintenance, and high reliability make NCSs the future of industrial control systems.

However, the insertion of communication networks into control systems will inevitably induce network delays, packet dropouts, and other network-induced characteristics [4–6], which possibly lead to system performance deterioration and even instability. Therefore, investigating the effects of network-induced delays and packet dropouts on NCSs has received considerable attention in the last decade [7–9]. There have been some nice results available in the existing literature. For example, the bounds on the maximum allowable transmission interval (MATI) and the maximum allowable delay (MAD) that guarantee the stability of NCSs in the presence of communication constraints were obtained in [10]. The design of proportion integration differentiation (PID) controllers for NCSs with polyhedral uncertainties was studied in [11]. The stability and state feedback controller design for continuous-time

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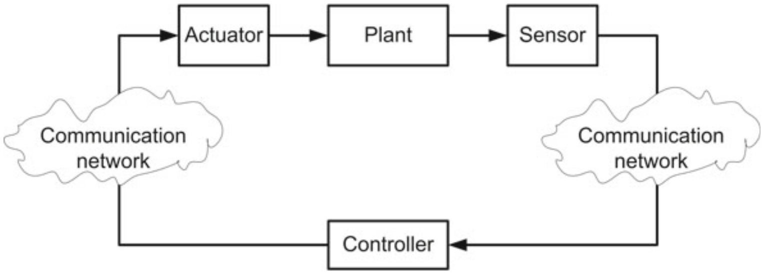

Fig. 1.1 The typical structure for an NCS

NCSs were considered in [12]. Based on information about the lower bound of network-induced delays, the design of robust H_∞ controllers for uncertain NCSs was addressed in [13]. The network-based H_∞ control problem was considered in [14] by applying a stochastic delay system approach. The stability analysis and controller design for NCSs with successive delay components in the state were investigated in [15]. A Lyapunov-Krasovskii functional was constructed in [16] to obtain some delay-dependent stability criteria. A controller design method for NCSs with nonlinearity was proposed in [17] by introducing an extended Jensen inequality. Integrated design of controller and communication sequences for NCSs under consideration of medium access limitations and measurement quantization was addressed in [18]. In [19], a general framework for analyzing the stability of general nonlinear NCSs with disturbances in the setting of L_p stability was provided. A tradeoff between the MATI, the MAD and the quantization parameters for an NCS was provided in [20]. The problem of prediction-based NCSs design has also been paid much attention in [21, 22].

It should be mentioned that the results in [14–16, 23] lumped network-induced delays and packet dropouts into one item $i_{k+1}h - i_k h + \tau_{k+1}$, and the upper bound of $i_{k+1}h - i_k h + \tau_{k+1}$ was employed in stability analysis and controller design. Thus, it is difficult to distinguish the effects of packet dropouts from network-induced delays on the stability and stabilization of NCSs. Establishing the quantitative relationship between packet dropout probability and stabilization of NCSs will help to reduce the negative effects of packet dropouts, which deserves further study.

By using a Markov chain-based method, stability/stabilization of NCSs with packet dropouts were studied in [24, 25]. The Markov chain-based packet dropouts were concerned in [24] with the jumping probabilities of packet dropouts from mode i to mode j being known. On the other hand, for the purpose of avoiding the occurrence of network congestion, one should allocate enough network bandwidth to NCSs. However, the actually needed network bandwidth may be smaller than the mean bandwidth at most time, and larger than the mean bandwidth at least time. Since the utilization of network bandwidth demonstrates such a non-uniform distribution characteristic, network-induced delays and packet dropouts, which are induced by network congestion and data packet collision, may be non-uniformly distributed. The non-uniform distribution characteristic of network-induced delays has been considered in [26–28]. To improve the admissible upper bound of consecutive packet dropouts, one should take the non-uniform distribution characteristic of packet dropouts into account.

Notice that the systems considered in [11, 18, 29, 30] are sampled with a constant sampling period. For control systems, the sensor supposedly samples over a fixed nominal period. However, computer loads, networks, and sporadic faults may lead to sampling period jitter inevitably. Recently, there have been considerable research efforts on time-varying sampling periods [31, 32]. For example, the problem of robust H_∞ control for sampled-data systems with probabilistic sampling periods was investigated in [33]. The output tracking control for NCSs with switched sampling periods was studied in [34]. However, if the sampling period is time-varying and varies on an interval, the switched sampling period-based design methods in [33, 34] are not applicable. On the other hand, the results in [31, 32, 34] are based on the discretization of continuous-time systems. If the actuator receives more than one control input during a sampling period, such a discretization process leads to much modeling and design complexity. For continuous-time NCSs under simultaneous consideration of network-induced delays, packet dropouts, and interval time-varying sampling periods, how to guarantee robustness to small variations of the sampling period and avoid the design complexity induced by discretization are of paramount importance.

1.2 FDF Design for NCSs

For NCSs, the occurrence of sensor faults or actuator faults is usually unavoidable. Then, it is of paramount importance to study how to detect the occurrence of faults in time. The fault detection for traditional control systems has been paid much attention and some interesting results have been reported, see [35–37] and the references therein. On the other hand, some nice results dealing with fault detection for NCSs have been obtained. For example, the network-based robust fault detection problem for discrete-time Takagi-Sugeno (T-S) fuzzy systems was addressed in [38]. The problems of fault detection, isolation, and estimation for discrete time-varying networked sensing systems were studied in [39]. Robust fault estimation for NCSs with network-induced delays was investigated in [40]. The fault detection of linear systems over networks with bounded packet dropouts was addressed in [41]. The problem of fault detection in finite frequency domain for NCSs was investigated in [42, 43]. A method for the fault detection of a nonlinear NCS was proposed in [44]. Fault detection of NCSs subject to uncertain time-varying network-induced delays was considered in [45]. A so-called packet-based periodic communication strategy for designing optimal observer-based residual generators was proposed in [46]. It should be mentioned that discrete-time systems are considered in [38, 39, 42, 44], while discretized NCSs are considered in [41, 43, 45]. Moreover, packet dropouts and/or network-induced delays are neglected in some of the above-mentioned works. For continuous-time NCSs considering packet dropouts and network-induced delays simultaneously, how to propose an appropriate observer-based FDF design scheme is interesting and practically valuable.

For NCSs with faults, the feasible fault signals are included in the measurement outputs $y(t_{k-1})$, $y(t_k)$, ..., where k denotes a positive integer, and $y(t_{k-1})$, $y(t_k)$, ... are adopted by the FDF to detect the occurrence of faults. For a specific time interval $[t_k + \tau_k,\ t_{k+1} + \tau_{k+1})$, where t_k and τ_k denote the sampling instant and the length of the network-induced delays, respectively, if we combine the recently received measurement output $y(t_k)$ and the formerly received measurement output $y(t_{k-1})$ together, which is named as data reconstruction in this monograph, and transmit the data reconstruction-based measurement outputs to the FDF, enlarged fault signals will be received by the FDF and the fault detection time will be reduced correspondingly. However, such a data reconstruction scheme has not been taken into full consideration.

For continuous-time NCSs with $t \in [t_k + \tau_k,\ t_{k+1} + \tau_{k+1})$, the artificial delay $\tau(t) = t - t_k$, which is named as an interval time-varying delay, is usually introduced to study stability/stabilization of considered systems. Suppose that $\tau(t) \in [\tau_m,\ \eta)$, where τ_m and η denote known constants. Divide $[\tau_m,\ \eta)$ into ρ equidistant time intervals with ρ denoting a given positive integer. One can see that for a specific instant t, $\tau(t)$ can not be included simultaneously in two different time intervals derived above. In what follows, we refer to such a phenomenon as mutually exclusive distribution. When dealing with integral inequalities for products of vectors, how to make full use of the mutually exclusive distribution characteristic of interval time-varying delays to derive less conservative results is of paramount importance.

1.3 Scheduling Protocol Design for NCSs

Note that most of the results mentioned above are concerned with stability and stabilization problems by assuming that system states are available. That is, the obtained results are only applicable for systems whose states are measurable. However, in the practical power systems and rougher flotation process, it is complicated to measure system states directly [47, 48]. As an alternative method, stability and stabilization problems of NCSs with output measurements have motivated a lot of interesting research, see [49, 50].

In the literature, single packet transmission is a general assumption [51]. This implies that all the measurements and control inputs are packaged into one data packet. However, it is generally unrealistic in many applications where the nodes are distributed over a large physical area. Therefore, it is interesting to study the problem of multiple packets transmission. In the scenario of multiple packets transmission, if the network bandwidth is limited, the node collision problem is unavoidable. To tackle the node collision problem, some scheduling protocols, such as try-once-discard (TOD) protocol [52], round-robin (RR) protocol [53, 54], and stochastic protocol [55, 56], are proposed to determine which nodes can access the communication network. In general, the TOD protocol and stochastic protocol can provide better system performance than the RR protocol. In the TOD protocol, the node with the largest weighted error gets the permission to access the communication network, whereas the stochastic protocol usually determines the transmission node via Bernoulli or Markov chain process (called Markovian protocol). With the utilization of a scheduling protocol, some fundamental challenges for the stability analysis will arise. Thus, it is worthwhile to study how the scheduling protocol affects the stability of NCSs.

Recently, a few preliminary results have been reported on the stability issue with a scheduling protocol. For example, stability of NCSs under RR and TOD protocols was considered in [10] by using the hybrid system approach. It should be mentioned that, in the presence of a scheduling protocol, the hybrid system approach does not allow large communication delays which are larger than the length of a sampling period. To incorporate such large communication delays, the time-delay system approach for NCSs under scheduling protocols was developed in [52, 57–59]. Note that the aforementioned results only provide sufficient conditions for exponential stability with a supposition that the controller feedback gain should be known. If the feedback gain of a controller is not known a priori, the aforementioned methods are no longer applicable. Moreover, the effects of packet dropouts on the studied systems are ignored in [58, 59]. Based on the discussions above, for NCSs under a stochastic scheduling protocol and the nonideal network quality of service (QoS) (network-induced delays and packet dropouts), how to analyze the effects of packet dropouts and how to design output feedback controllers are still a challenging issue.

1.4 Network-Based Heading Control of UMVs

Heading control of ships is one of main concerns for marine applications [60, 61]. Accurate heading control, which can be achieved through the regulation of the rudder angle, is important for the routine operation and safe navigation of ships. However, ships are exposed to wave-induced disturbances, which inevitably leads to heading angle deviation and frequent regulation of the rudder angle. Thus, it is of paramount importance to study how to achieve accurate heading control and rudder oscillation reduction for ships exposed to wave-induced disturbances. In the existing literature, there are some nice results available dealing with heading control and controller design for manned ships. For example, Kalman filtering-based positioning and heading control for ships and offshore rigs were addressed in [62]. A family of passivity-based controllers for dynamic positioning of ships were presented in [63]. The implementation of genetic programming in designing a controller structure for a surface ship was studied in [64]. The control of underactuated ships was studied in [65–67]. The thrust loss suppression algorithm and marine thruster control were considered in [68] and [69], respectively.

Network-based control systems have attracted considerable attention in the last decade [70–72]. For recent developments, we refer readers to two recent survey papers [4, 73]. Due to the introduction of modern high-speed communication networks between UMVs and remote land-based/mother ship-based control stations, network-induced delays are usually very small, and sometimes they are negligible. As observed from [4, 73], network-induced packet dropouts, which are referred to as passive packet dropouts in this monograph, are usually regarded as the source of system instability and performance degradation. In this monograph, we take a different and novel view. We investigate whether or not intentional packet dropouts, which are referred to as active packet dropouts, can stabilize the UMV in network environments and provide satisfactory heading control. For some damping-like systems such as offshore structures [72, 74, 75], by purposely introducing a proper time delay, the internal oscillation of the systems can be reduced. Note that packet dropouts in network-based control systems can be described as a type of time delay. Therefore, actively dropping some control input packets purposely may reduce the heading angle deviation and the oscillation of the rudder angle of the UMV in network environments, which deserves an in-depth investigation.

1.5 FDF and Controller Coordinated Design for UMVs

The motion control of marine vehicles emerges as a topic of significant interest due to an increasing demand for higher accuracy, higher performance, and reliability in practical applications [60]. Some interesting research results are reported in the literature on heading control [76], roll stabilization [77], and control of underactuated ships [78]. Note that manned marine vehicles are studied in [60, 76–78]. The development of unmanned marine vehicles is particularly significant in providing cost-effective solutions to coastal and offshore problems. UMVs are widely used in monitoring, oil and pollution clean-up, scientific characterization, exploration, military operations such as mine sweeping and border surveillance [79, 80]. There are some nice results available dealing with the motion control of UMVs. For example, an approach based on Theta* algorithm was suggested in [81] to create paths for UMVs in real-time. The problem of accurate identification and learning control of ocean surface ships in uncertain dynamical environments was addressed in [82].

It should be pointed out that filtering and control for UMVs is usually based on a remote land-based or mother ship-based control station in network environments. Despite of advantages such as lower cost, more flexibility and higher reliability, introducing communication networks into control systems inevitably induces network delays and packet dropouts [83–86]. Thus, if a communication network is introduced between the UMV and the remote control station, such network-induced characteristics should be taken into full consideration.

Moreover, for UMVs in network environments, the occurrence of faults, such as the saturation, the stuck steering machine-type faults, and the noise-type faults, is usually unavoidable. Then it is of paramount importance to study how to detect the occurrence of faults in time. On one hand, fault-tolerant control and fault detection for traditional control systems have been paid much attention and some interesting results have been reported, see [87, 88] and the references therein. Note that an integrated fault detection and robust control scheme was proposed in [87] to attenuate the effects of disturbances and detect the actuator stuck faults. Based on the scheme in [87], the simultaneous dynamic observer-based robust control and fault detection problem for linear systems was investigated in [36]. The simultaneous fault detection and robust control scheme gets further development in [89] to deal with continuous-time switched systems. On the other hand, for NCSs, there are some nice results dealing with fault detection in the literature. For example, the problem of fault detection, isolation, and estimation for networked sensing systems was considered in [39]. Fault detection filtering for a discrete-time system considering network-induced nonlinear characteristics was investigated in [90]. For a UMV subject to faults, if the sampler-to-control station communication network channel-induced and the control station-to-actuator communication network channel-induced characteristics such as network-induced delays and packet dropouts are considered simultaneously, the measured output available to the FDF during a specific time interval is variable. This induces some difficulty for describing the measured output in a uniform form and constructing the corresponding networked system. Thus, for a UMV subject to faults, and the sampler-to-control station communication network channel-induced and the control station-to-actuator communication network channel-induced characteristics, how to establish a network-based model is practically valuable and still unresolved, which motivates the current study. Moreover, network-based FDF and controller coordinated design for the UMV is of paramount importance and still unresolved, which deserves deep investigation.

One can see from Sect. 1.2 that taking into account the mutually exclusive distribution characteristic of the interval time-varying delay $\tau(t)$ is helpful. When investigating network-based FDF and controller coordinated design for the UMV in network environments, how to make full use of the mutually exclusive distribution characteristic of $\tau(t)$ to derive more relaxed design criteria is important.

1.6 Dynamic Positioning of UMVs

Marine vehicles have found applications in broad areas including transportation, military operations, hydrographic, fishing, oil and gas exploration and construction, oceanographic data collection, and scientific characterization [91, 92]. There are some interesting results available concerning the motion control of marine vehicles, which cover research topics in roll stabilization [77], tracking control [78], heading control [76, 93], containment maneuvering [94, 95], mooring control [96], fault detection [97], model predictive control [98], and path planning [99]. Besides the topics mentioned above, dynamic positioning, which aims at regulating the horizontal position and heading of marine vehicles, has also attracted much attention in the literature [100]. For example, Kalman filtering-based positioning and heading control of ships were investigated in [101]. The semiglobally practically asymptotically stabilizing controller design for dynamically positioned ships was proposed [102]. Adaptive robust output feedback control for a marine dynamic positioning system (DPS) was investigated [103]. Output feedback control for a marine DPS was addressed [104]. By using multiple unidirectional tugboats, robust dynamic positioning of an unactuated surface vessel was studied [105]. In [106], robust controller design for dynamic positioning of ships and offshore rigs using H_∞ and mixed-μ techniques was considered. A novel continuous robust controller for dynamically positioned surface vessels with added mass terms was constructed [107]. A robust nonlinear control law for the DPS of ships subject to unknown time-varying disturbances and input saturation was proposed [108]. Quadratic finite-horizon optimal controller design for T-S fuzzy-model-based dynamic ship positioning systems was addressed [109]. As one can see, the T-S fuzzy-control-based approach, which is different from those in [100, 105–108], was adopted in [109] to describe the dynamic positioning of a marine vehicle. There is a growing interest in applying the T-S fuzzy control approach to deal with nonlinear control systems. The main characteristic of T-S fuzzy control lies in utilizing a linear system model to describe the local dynamics of each fuzzy rule [109, 110]. Then the abundant linear control methodologies can be adopted to investigate each linear model. Since the DPS of a marine vehicle is a complex nonlinear system, how to propose an appropriate modeling and control scheme to improve the dynamic positioning performance is practically valuable and attractive.

Dynamic positioning for a UMV is usually based on a remote land-based/mother ship-based control station. The UMV, the remote land-based/mother ship-based control station, and communication networks constitute a network-based control system. Despite of advantages of network-based control, introducing communication networks into control systems may induce packet dropouts, delays, and packet disordering [111–114]. For the networked DPS of a UMV, how to take sampler-to-controller and controller-to-actuator packet dropouts, network-induced delays, and packet disordering into account, and to establish network-based T-S fuzzy models are of paramount importance and far from being resolved.

For a T-S fuzzy system, if a communication network is introduced between the controlled plant and the controller, the membership functions of the controlled plant and the controller are not synchronous, and such a characteristic is neglected in [23]. The asynchronous difference between the normalized membership function of the controlled plant and that of the controller was taken into consideration in [115, 116]. Moreover, for the T-S fuzzy-control-based DPS of a UMV, the T-S fuzzy model is closely related to the variation scope of the yaw angle. Then how to take into account the variation scope of the yaw angle and the asynchronous difference between the normalized membership function of the UMV and that of the controller, and to derive a novel stability criterion are practically valuable.

In practical situations, the controlled plant states are not always measurable. Thus, it is of paramount importance to study the observer-based control scheme for T-S fuzzy systems, and some nice results are available in the literature [117–120]. Note that only the sensor-to-observer network-induced delays are considered in [117], while packet dropouts and the controller-to-actuator network-induced delays are not considered. The work in [118] assumed that updating instants of the control input and the measured output are the same. In fact, if time-varying network-induced delays are considered, such an assumption may not be applicable. Moreover, packet dropouts are not considered in [118]. The Bernoulli stochastic process was adopted in [119] to describe packet dropouts in the sensor-to-observer channel and the controller-to-actuator channel with network-induced delays being neglected. The problem of observer-based output feedback control for T-S fuzzy systems under decentralized event-triggering communication was discussed in [120] with packet dropouts and network-induced delays being neglected. For the observer-based T-S fuzzy DPS of a UMV, taking into account sampler-to-controller and controller-to-actuator network-induced characteristics will lead to much modeling and controller design complexity. How to solve these issues is practically valuable.

1.7 Networked DOF Control of UMVs

Manned/unmanned marine platforms can provide cost-effective solutions to coastal and offshore problems. Compared with manned marine vehicles, unmanned ones can provide more flexibility in practical applications [76]. Some interesting results dealing with UMVs were reported in [121–124]. When carrying out tasks such as scientific characterization and exploration, a UMV may be stopped and anchored. However, external disturbances, such as waves, wind, and current, may induce the oscillation of the yaw velocity error and the yaw angle of the UMV, where the yaw velocity error denotes the difference between the actual yaw velocity and the constant yaw velocity reference. Obviously, the oscillation of the yaw velocity error and the yaw angle is not desired in practical applications. For a UMV, how to propose an appropriate control scheme to attenuate the oscillation amplitudes of the yaw velocity error and the yaw angle is practically valuable and attractive.

Based on a remote control station, one can control the motion of a UMV in network environments. Note that state feedback control of NCSs was studied in [125, 126]. In some practical situations, controlled plants' states may not be always measurable. Thus, it is significant to study observer-based control of systems under consideration [71, 97, 127] and dynamic output feedback control of systems under consideration [50, 116, 128]. For a UMV, if the surge velocity, sway velocity, and the yaw velocity are not measurable, how to propose an appropriate dynamic output feedback controller (DOFC) design scheme to attenuate the oscillation amplitudes of the yaw velocity error and the yaw angle is significant and has received little attention in the literature.

The non-uniform distribution characteristic of interval time-varying delays was considered in [129, 130] to study the stabilization of systems. For the UMV in network environments, packet dropouts and network-induced delays may be non-uniformly distributed. Note that the non-uniform distribution characteristic of packet dropouts and network-induced delays can be implied by the non-uniform distribution characteristic of an interval time-varying delay. If such a characteristic is considered, how to establish network-based models for the UMV, and how to construct appropriate integral inequalities for products of vectors which are introduced in DOFC design are challenging problems.

1.8 Cooperative Target Tracking of Multiple UMVs

Some typical motion control issues for UMVs such as the heading control [131, 132] and dynamic positioning [1, 108, 133, 134] have been reported in the literature. Recently, the target tracking [135–137], trajectory tracking [138, 139], and path following [140–142] have garnered widespread attention due to their extensive marine applications in military reconnaissance, environmental monitoring, ocean exploration, offshore inspections, and so on. In particular, maritime target tracking, whose purpose is to drive corresponding marine vehicles to track a moving target, has received much attention [143–146]. For an autonomous underwater vehicle, a prescribed performance bound method was presented to achieve target tracking and guarantee the transient performance [144]. For an autonomous robotic vehicle, a switched logic-based control strategy was proposed to address the target tracking problem by utilizing range-only measurements [145]. Note that the above-referenced results mainly involve one-to-one tracking, i.e., one marine vehicle tracks one target. However, some maritime target tracking missions require the cooperation of a fleet of UMVs, which can improve flexibility, robustness, and efficiency of mission completion. For a group of UMVs, the cooperative target tracking problem is far from being resolved. Therefore, how to achieve cooperative target tracking for multiple UMVs deserves in-depth investigation.

In most of cases, it is assumed that both position and velocity information of maritime targets can be either measured or received by follower UMVs [135]. For one UMV, however, it is costly and difficult to obtain the accurate velocity of the target [147, 148]. Thus, how to track a target by using only its position information measurement is of paramount importance. On the other hand, in a practical target tracking system composed of multiple UMVs, some of the UMVs can not obtain the target information due to restrictions of distances and/or external environments. To address this problem, some existing results adopt leader-follower tracking control schemes (see in [135, 136, 147, 149]), which can be sketched as "UMV 1 tracks the target, UMV 2 follows UMV 1, UMV 3 follows UMV $2\cdots$". This means that one UMV only has one neighbor. Specifically, a UMV can only track the target or follow another UMV by measuring/receiving information from it. In this case, if a communication link or a measuring device fails, the cooperative target tracking mission may fail. In the field of multi-agent system control, the distributed control scheme provides a solution to this dilemma [150–153]. However, how to apply the distributed scheme to conduct the cooperative target tracking is still challenging, not to mention in the case of lacking the target's velocity information.

The interaction between the target and the UMVs can be described by a communication network. In some existing results concerning cooperative control of multiple UMVs, interaction network topologies are assumed to be fixed [154–156].

In practical maritime tracking applications, the connectivity of the corresponding interaction topology may switch due to link failures, sensor incapabilities, channel attenuation, and alteration of missions. This heightens the need for investigating the cooperative control problem of multiple UMVs under switching topologies. Actually, the cooperative control of multi-agent systems under switching topologies has been studied in the existing literature [157–160]. However, these results can not be directly extended to deal with the cooperative control of multiple UMVs. For a tracking system composed of multiple UMVs, the cooperative target tracking problem under switching topologies has not been adequately addressed hitherto.

1.9 Contributions of the Monograph

Based on systematic results for stability analysis, stabilization, and fault detection of NCSs, this monograph focuses on the heading control, fault detection, dynamic positioning, dynamic output feedback control, and cooperative target tracking of UMVs. The packet dropout separation method, the data reconstruction scheme, the active packet dropouts approach, and the cooperative target tracking scheme are proposed to deal with the stabilization of NCSs and the motion control of UMVs. More specifically, the main contributions of this monograph are highlighted as follows.

- A packet dropout separation method is proposed to separate packet dropouts from the lump sum of network-induced delays and packet dropouts. A new NCS model is established correspondingly by taking interval time-varying sampling periods and the non-uniform distribution characteristic of packet dropouts into full consideration. The quantitative relationship between packet dropout probability and stability/stabilization of the NCS is established by constructing a new packet dropout decomposition-based Lyapunov functional. The stability and stabilization criteria can guarantee robustness of the NCS to small variations of sampling periods.
- New closed-loop models for a continuous-time NCS with actuator faults are established by proposing a data reconstruction scheme. The mutually exclusive distribution characteristic (which introduces less conservatism) of interval time-varying delays is made full use to deal with integral inequalities for products of vectors. The observer-based FDF design criteria are achieved. The designed FDFs can guarantee the sensitivity of the residual signal to faults.
- A stochastic impulsive delayed system is constructed for an NCS under consideration of an IID scheduling protocol, network-induced delays, and packet dropouts. The effects of network-induced delays and packet dropouts are taken into full consideration. An optimization algorithm is presented to determine the optimal multi-sensor protocol scheduling parameters and the output feedback controller gains.
- A novel network-based model is established for a UMV by constructing a heading control error system and purposely dropping some control input packets received by the steering machine. Whether or not active packet dropouts can stabilize the