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Survey Article

A Survey of Decentralized Fault-Tolerant Control Systems

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***Abstract*— As technology has progressed, the demand for a system's reliability and safety under potential faults is an essential issue. Fault-tolerant control systems strive to handle failures of the system components and preserve stability while reducing performance degradation to a tolerable degree. Therefore, fault-tolerant control systems become an urgent necessity, especially for large-scale systems, due to their complexity, which raises the possibility of malfunctions. The main contribution of this paper is to present a comprehensive review of decentralized fault-tolerant control for large-scale systems, including the latest techniques in this field. Several strategies were compared based on the development of decentralized fault-tolerant control techniques used to address the impact of faults on such systems.**

***Index Terms*— Decentralized control, large-scale systems, fault-tolerant control system, advancement techniques of fault-tolerant control.**

I. INTRODUCTION

Researchers focus extensively on fault-tolerant control (FTC) systems within advanced control strategies because of their critical importance in creating dependable and safe systems [1]. The continual development in this field has resulted in several beneficial review papers that provide an overview of the most novel techniques. Patton provided a comprehensive survey of FTC strategies in 1997, including an analysis of the fundamental difficulties in FTC design [2]. The article [3] gave an overview of studies of FTC constructed based on assessing and reconfiguring the current state in the field. A wide range of control systems with potential faults was analyzed using the FTC approach with fault detection and isolation (FDI) technique [4]. The reviews [5-8] study the development of passive and active FTC systems, including their problems and benefits. The latest techniques of FTC systems were surveyed in [9]. The incorporation of passive and active FTC was examined in [10], which briefly evaluated the aerospace system's FDI and FTC techniques. In [11-14], the FDI technique is divided into four categories: knowledge, signal, model, and the hybrid/active methods extensively utilized with FTC systems.

The swift advancement of technology has become the dependability and safety of systems in the event of fault cases is a clear and pressing concern [15, 16], particularly for extensive interconnected systems, which are complex and high-dimensional entities characterized by nonlinearity and uncertainty. During operation, external disruptions increase the probability of a system failure. As a result, it is difficult to build and manage such systems with reliable control [17]. Among the practical systems used in large-scale systems (LSSs) are wind turbines [18], aviation systems [19], mechanical systems [20–22], urban traffic, and economic systems [23] and [24] gives an extensive literature survey of a large-scale system (LSS). Three basic control mechanisms exist for LSSs: centralized, decentralized, and distributed control. Researchers are particularly interested in decentralized control since each subsystem relies on local information without sharing it with other subsystems, as illustrated in subsection 2.2. Some topics on decentralized control were reviewed in [25] and [26]. Although great efforts have provided a comprehensive survey of FTC and decentralized control, most studies reviewed each of the FTC systems and decentralized control separately, without providing a review, when integrating them to construct a robust FTC for interconnected LSSs. Thus, the main objective of this study is to present a comprehensive review of the decentralized FTC systems, which covers the latest techniques used to create a control system more resiliently.

The rest of this study is arranged in the following manner. Section 2 presents an overview of LSS. Section 3 discusses the FTC system. Section 4 reviews the development of a decentralized FTC system. Finally, the conclusions are presented in Section 5.

II. LARG-SCALE INTERCONNECTED SYSTEMS

The increasing demand for quality productions with economic efficiency has led to modern systems that are increasingly complex and large-scale. Generally, an LSS comprises a set of subsystems coupled by interconnections.

All systems work together to achieve a common goal, with each subsystem assigned to carry out a specific task. One of the most challenging aspects of such systems is how to handle the interactions between the subsystems [27]. The authors in [28] used a combination of the sliding mode technique and the Luenberger observer with a state feedback control to handle the effects of the interactions, but this work does not deal with the FTC systems. In [29], adaptable laws are used to estimate the impacts of unknown interconnections to discover the equivalent of these interconnections between subsystems.

The term "large-scale interconnected system" is employed in certain texts just to show how the LSS's subsystems are related to one another. The phrase large-scale system refers to a system that cannot be resolved in a single step, rather than a specific system. Otherwise, systems that include connections between subsystems are referred to as "Interconnected Systems". After the system is divided into smaller subsystems, a so-called interconnected system will be created. In a different way, the problem will be broken down into smaller, easier subproblems that can be handled separately or in weak coupling, making it simple to eliminate for efficient operation.

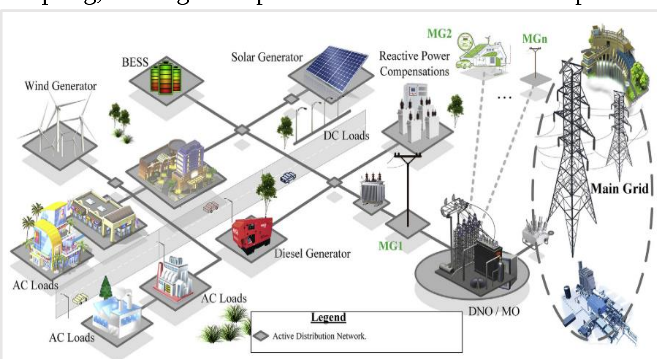

Fig. 1. Example of LSSs [30].

A. The mathematical analysis of LSSs

A mathematical model of linear interconnected LSSs composed of (n) subsystems can be represented in (1) to give a general overview of these systems' composition [24]:

$$\dot{x}_i = A_i x_i + B_i u_i + \sum_{j=1,\ldots,n} A_{ij} x_j + \sum_{j=1,\ldots,n} B_{ij} u_j.$$
$$y_i = C_i x_i + \textstyle\sum_{j=1,\ldots n} C_{ij} x_j. \tag{1}$$

Where $x_i, u_i,$ and y_i represents the state, input vector, and output vector, respectively. Otherwise, the matrices $A_{ij}, B_{ij},$ and C_{ij} indicate the interconnection of the system, input, and output, respectively. When all subsystems are combined, the overall system can be represented as:

$$x = Ax + Bu.$$
$$y = Cx. \tag{2}$$

The augmented matrices of the input and output are described as follows [24]:

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1(n-1)} & A_{1(n)} \\ A_{21} & A_{22} & & A_{2(n-1)} & A_{2(n)} \\ \vdots & & \ddots & \vdots & \\ A_{(n-1)1} & A_{(n-1)2} & \cdots & A_{(n-1)(n-1)} & A_{(n-1)(n)} \\ A_{(n)1} & A_{(N)2} & & A_{(n)(n-1)} & A_{(n)(n)} \end{bmatrix}$$

$$B = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1(n-1)} & B_{1(n)} \\ B_{21} & B_{22} & & B_{2(n-1)} & B_{2(n)} \\ \vdots & & \ddots & \vdots & \\ B_{(n-1)1} & B_{(n-1)2} & \cdots & B_{(n-1)(n-1)} & B_{(n-1)(n)} \\ B_{(n)1} & B_{(n)2} & & B_{(n)(n-1)} & B_{(n)(n)} \end{bmatrix}$$

$$C = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1(n-1)} & C_{1(n)} \\ C_{21} & C_{22} & & C_{2(n-1)} & C_{2(n)} \\ \vdots & & \ddots & \vdots & \\ C_{(n-1)1} & C_{(n-1)2} & \cdots & C_{(n-1)(n-1)} & C_{(n-1)(n)} \\ C_{(n)1} & C_{(n)2} & & C_{(n)(n-1)} & C_{(n)(n)} \end{bmatrix}$$

Due to dimensionality concerns, a decentralized solution based on local controllers for LSSs was desired. In many cases, the computations needed to control the total system develop more rapidly than the system's dimensions. The centralized controller is considered another issue because it is extremely sensitive to the interconnection where it can simply become unstable due to subsystem modifications. Therefore, controlling LSSs with centralized controllers is complicated. The following subsection discusses the control strategies of LSSs, including their advantages and disadvantages.

B. *The LSS's control methods*

Three fundamental control techniques are present in LSSs: decentralized, centralized, and distributed control., as shown in Figs. 2, 3, and 4, respectively. The conventional method for managing interconnected systems has a centralized controller. This technique requires substantial information exchange between subsystems, hence elevating both complexity and expense. [31-34]. Furthermore, if the centralized control malfunctions, the system forfeits its capacity to regulate the subsystems, resulting in overall instability.

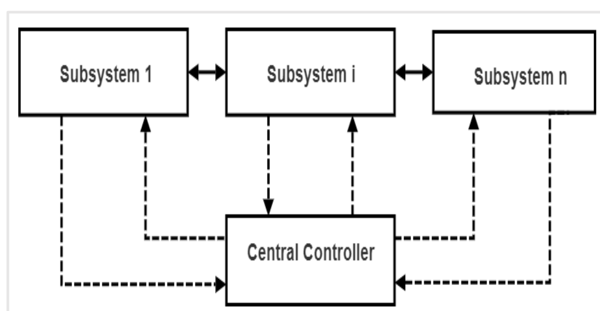

Fig. 2. Centralized management of interconnected systems.

The main motivation for designing a decentralized scheme is that the information exchange between the subsystems is not required. As a result, the local subsystem controllers are quite basic and only use data that is locally available.

Therefore, the researchers are interested in the decentralized control system as it reduces the computational burden and storage requirements and easily corrects errors [35, 36].

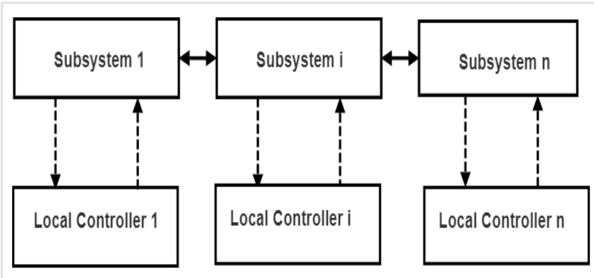

Fig. 3. Decentralized management of interconnected systems.

In contrast, the distributed and decentralized control system is similar in the main feature, where each subsystem has its own controller instead of a single controller, ensuring users have equitable access to data.

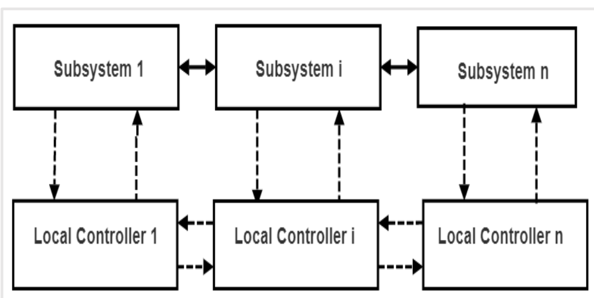

Fig. 4. Distributed management of interconnected systems.

Fig. 5 explains how to build a control strategy and the several mathematically representable kinds of interconnected systems.

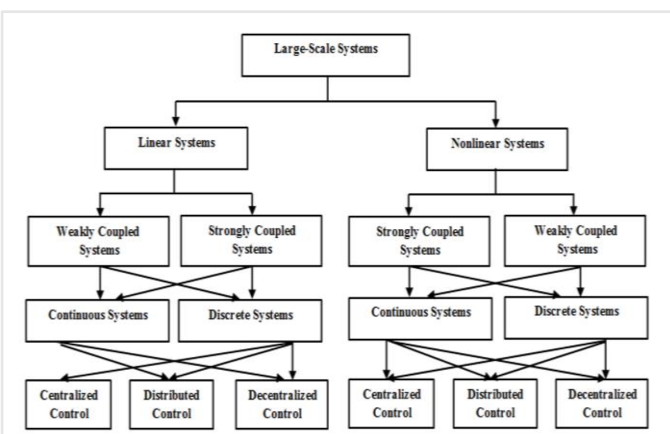

Fig. 5. Categorization of linked systems and control mechanism.

It is simple to create a controller for each system in the case of weakly coupled subsystems by isolating each subsystem from the other ones and ignoring the value of interactions between them. In contrast, these interactions cannot be ignored if the subsystems are strongly coupled and should be considered when designing the controller [37]. The absence of information between subsystems is challenging when designing the controller and observer, as discussed in [38-40]. Some techniques have been considered when designing a decentralized controller for LSSs to tackle this challenge, like fuzzy logic control [41], [42], neural networks [43], [44], adaptive control [45], control of blended learning [46], surface control that is dynamic [47].

C. A survey approach to decentralized control of LSSs

Constructing decentralized control laws that solely use measurable local states to achieve large-scale goals is economical and effective in dealing with dimensionality, uncertainty, and restricted access to information. The features and advantages of several decentralized control methods were reviewed as follows:

- **Decentralized approach with intelligent systems:** Fuzzy logic and neural networks are often utilized to construct decentralized controllers or estimate LSSs with uncertainty and nonlinearity. The authors in [48] created a fuzzy decentralized control technique for dynamic systems that operate with time delays, external disturbances, and without measurements to enhance the closed-loop system's performance. [49] A decentralized adaptive fuzzy control design based on the voltage control method approximates a fuzzy error compensator, whereby estimated fuzzy faults are taken into account to boost asymptotic tracking efficiency. A decentralized fuzzy controller with finite time is developed in [50] to oversee interconnected, nonlinear systems with output restrictions. An adaptive decentralized fuzzy control was proposed in [51] with time delay employed to estimate nonlinear systems.

  An adaptive neural network control technique for mismatched and unknown connections has been developed in [52]. A decentralized control based on a neural network was discussed in [53], where the neural network was used to estimate the states with the backstepping technique.

- **Decentralized approach with robust control:** Any practical system's aging and shifting operational conditions will cause ambiguity, disturbances, including LSSs, and modifications to the dynamics of the system. Therefore, when creating the closed-loop control system, the controller design needs to take system stability and robustness into account. Harno et al. [54] developed a reliable H∞-based decentralized controller for uncertain nonlinear systems that is capable of managing connections between known nonlinearities and subsystems without considering them to be uncertainties. [55] established a novel strategy for decentralized control to stabilize a class of continuous LSSs. Then, by employing an integral policy iteration, they expanded their strategy to include unknown dynamic systems [56].

A chaotic nonlinear interconnected system with robust adaptive control was discussed in [57]. A decentralized proportional-integral (*PI*) control technique for interconnected systems was proposed by Yi and Zheng in [58].

- **Decentralized approach with model predictive control (MPC):** The MPC is a common technique for constructing a decentralized control structure [59], [60]. There are numerous reasons why it has become widespread. The MPC technique predicts the system output and seeks iteratively to find the best solution. Secondly, real-world applications are more likely to use system restrictions like actuator and sensor cost, etc, while tackling the optimization problem. In addition, the literature contains a variety of decentralized MPC techniques that can be used in LSSs [61], [62].

- **Decentralized approach with stability characteristic:** The literature has extensively addressed the topic of decentralized controller stability [63-65]. [63] Declare that a reliable controller of super-twisting sliding mode with the multi-input, multi-output system was developed. When the bounded disturbance is present, [28] provides the closed-loop stability for interconnected systems with unknown interconnections. An observer-based decentralized control output tracking issue for LSSs has been discussed in [65].

D. Faults in LSSs

It is crucial to make the distinction between failure and fault clear. A fault occurs when at least one distinctive system attribute or parameter deviates from acceptable operating conditions. Failure, on the other hand, occurs when a system operation or component completely fails. It indicates that the proposed system no longer serves the purpose for which it was designed [37]. Generally, the FTC will consider a "workaround" to be a fault, allowing the faulty system to continue operating. Because the breakdown is irreversible, the system or component must be turned off immediately [1], [66].

Faults are categorized according to where they occur within the system, as shown below [67]:

- Actuator fault $f_a(t)$: This failure results from a difference in the control input u(t) employed in a system that is fully or partially regulated.
- Sensor fault $f_s(t)$: shows that the current system generates inaccurate estimations. The issues can be categorized as either partial or complete sensor faults. The measurements obtained won't match the physical specifications needed for the sensor. In the case of the incomplete sensors, these measurements provide erroneous information about the necessary physical properties.

- Process fault $f_p(t)$: Due to faults in the system's structure or parameters, this failure has a direct effect on the output characteristics and system parameters. Thus, it encompasses a wide range of possible faults.

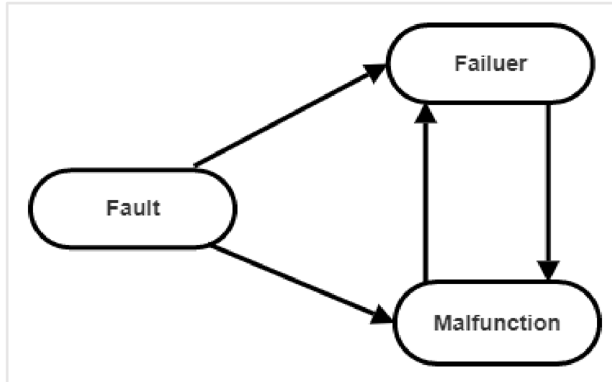

Fig. 6. The relationship between malfunction, failure, and fault.

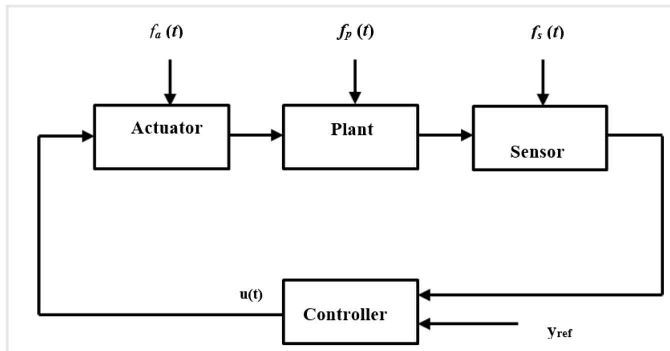

Fig. 7. Classification of faults based on their location.

E. The main difficulties in LSSs

According to several researchers, uncertainty, dimensionality, delay, and information constraints are the fundamental causes of large-scale system complexity and difficulty [68], [69], which can be defined as follows:

- **Uncertainty**: A mathematical model cannot accurately describe the total system. Uncertainties arise from a lack of complete system identification, control signals, or unknown disturbances. A system's management may also introduce uncertainty by gathering or simplifying models.

- **Dimensionality:** A system's dimensionality can be pretty big. Many significant inputs and states are present in a single LSS that a one-shot control strategy cannot easily handle. Some decomposed LSSs have many subsystems that need to be analyzed for structure and resilience before being used as effective control systems.

- **Constraints with the information**: Because of the dimension issue, and numerous decision-makers must manage the subsystems. None of these decision-makers has a thorough understanding of the system. The closed-loop system's controller is an example of decision-makers using only local information.

Analysis and composition cannot be effectively completed by a single-step controller. Consequently, instead of using a single controller, several independent local controllers that supervise the system [70].

III. Fault Tolerance Control (FTC) Systems

Fault tolerance refers to a system's ability to continue operating despite the failure of one or more components. Prolonged operation can result in numerous failures, rendering these systems unstable. Consequently, maintaining operation despite the occurrence of a problem is crucial for all systems, especially interconnected systems. [71]. So, the requisite goal is to establish a closed-loop system with an FTC or observer that accounts for component faults to achieve a stable system with a minimal decrease in nominal performance [72-80].

FTC methods can be categorized as either passive or active. When designing the passive FTC (PFTC), a closed-loop system and a fixed controller are necessary to manage all potential faults and guarantee a minimum level of performance. [72], [81]. Alternatively, a supervisory system outlines how to fix a system's faults by altering parameters and control structures after the active FTC (AFTC) uses detection techniques to identify possible faults. [82]. With its more sophisticated controllers, AFTC might perform better than PFTC. Nonetheless, employing AFTC presents considerable disadvantages, such as the resultant complexity of the controller and the incapacity to identify defects arising from external disruptions [83].

For designing the PFTC, many methodologies are used, such as the approach of sliding mode control (SMC) [84-86], H∞ [87-89], fuzzy logic control [90] and [91], Linear Quadratic control [92], Lyapunov-based control [93], and control allocation [94], [95]. The articles in [96–99] constructed the AFTC controllers based on the accommodation of the fault. The data-driven controllers in [100] and the SMC [101-103] are also mentioned.

Fig. 8 describes the AFTC approach, which is separated into two types of processes: projection and control reconfiguration-based approaches. The primary difference between the two methodologies is in the employment of control design reconfiguration or adaptation. The last-mentioned includes the computation of new controller parameters upon degradation in control using the reconfigurable control.

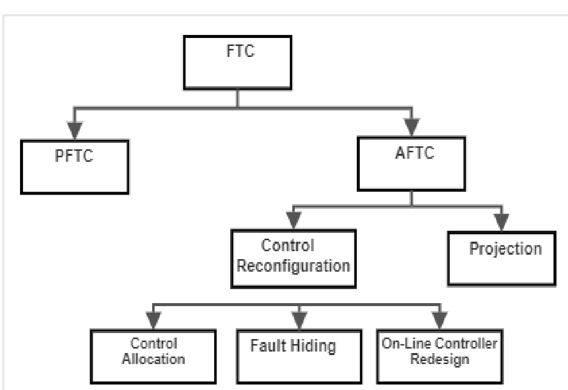

Fig. 8. General classification of the FTC system.

For passive FTC systems

- It’s hard to account for the huge number of potential faults.
- Implementation is straightforward.
- Unable to handle unexpected faults.

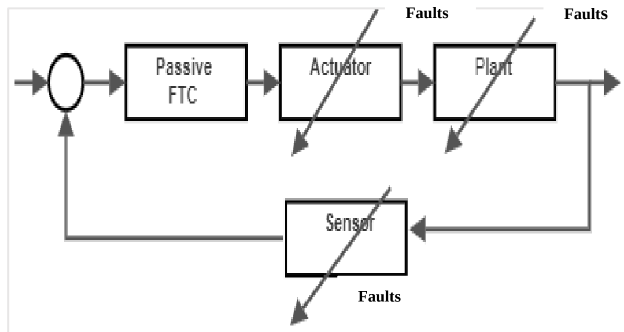

Fig. 9. Passive FTC system.

For active FTC systems

- Able to handle a variety of faults possibility.
- It’s more complicated.
- Reconfiguration of controllers in real-time.

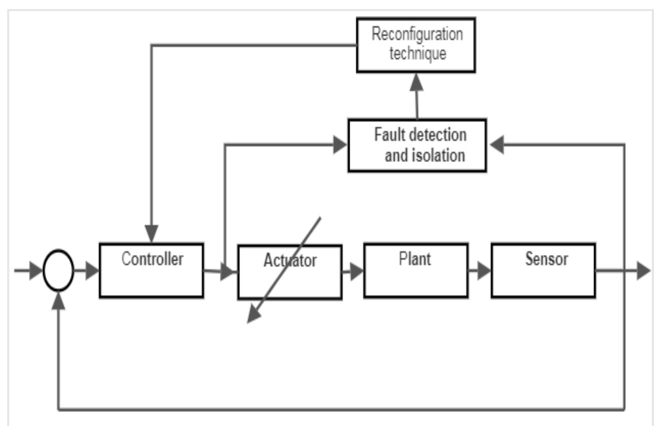

Fig. 10. Active FTC system.

In large-scale interconnected systems, components may experience a sudden fault, or one of the subsystems may undergo failure. Consequently, the occurrence of such failures in one or more subsystems causes poor performance and instability in the whole system. Also, the effects resulting from the interactions make the faults estimation inaccurate, whereas most research methods deal with only individual types of faults, either without uncertainties or with minimal uncertainties. Therefore, it is essential to design an FTC that ensures reliable system performance against the individual failure of subsystems [104-106].

Briefly, the key design challenges for the local subsystem stem from the nature of subsystem interconnections, uncertainties, and time delays, also as the faults of the sensor, actuator, or other components. System dimensions with failure propagation effects have increased complexity, especially when all subsystems fail together.

V. DECENTRALIZED FTC SYSTEMS

Controllers must be able to handle faults to restore maximum system efficiency. Thus, FTC has become an interesting and challenging topic [107].

In recent decades, many studies have focused their interest on FTC-based decentralized controllers. Researchers presented an adaptive fuzzy decentralized FTC for nonlinear LSSs as robust feedback by integrating the technique of backstepping and the theory of nonlinear FTC [108]. The issue of adaptive decentralized FTC for uncertain LSSs, including actuator faults and disturbances, was discussed [109]. The problem of a decentralized FTC system with sensor and actuator faults was inspected in [110]; with the utilization analysis technique of the Lyapunov absolute value function. This technique bounds all signals and converges each subsystem's error tracking zero. The decentralized FTC for nonlinear interconnected systems was investigated in [111] using algebraic graph theory [112], which presents an entirely new technique for constructing a decentralized observer-based controller with nonlinear terms of interconnection.

[113] Using a reduced-order observer to estimate the sensor and actuator faults simultaneously. [27] The FTC design issue was considered based on the H∞ observer for three faulty situations: sensor only, actuator only, and actuator and sensor faults. The authors in [114] examine the large-scale randomized for observer-based decentralized control with multiple delays. In [115], problems arising from Takagi-Sugeno fuzzy models involving actuator and sensor inputs have been studied. [116] The decentralized predictor based on feedback control was developed to compensate for delays in LSSs. [117] A new observer is then instructed to generate the N-error dynamics through information from the induction fault estimation (k - 1), where the suggested observer can better realistically display the shapes and sizes of the sensor and actuator failure. The design of decentralized adaptive fuzzy was used in [118], experienced external disruptions and actuator failures to maintain the formation's tracking control while flying. The study in [119] offers a unique method for discrete nonlinear decentralized FTC by using MPC.

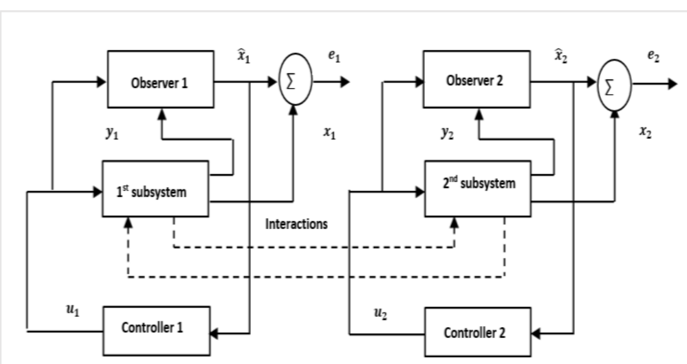

Fig. 11. Decentralized control based on observers with unknown subsystem interactions.

An FTC technique based on the sliding mode observer (SMO) and adaptive decentralized fuzzy is suggested in [120] for the sensor fault for the reconfigurable manipulator. A restricted FTC for reentry of near-space vehicle (NSV) is proposed in [121] to employ the sliding mode, command filter, backstepping strategy, and FDI information. The model of adaptive approximation in [122], which approaches the upper boundary of the disturbance function adaptively, is used to build a decentralized FTC system.

The technique of active decentralized FTC based on H∞ is used in [123] to reconfigure the manipulators with synchronous sensor and actuator faults. The topic of event-triggered decentralized uncertain nonlinear LSSs tracking with unanticipated actuator faults is investigated [124].

A novel decentralized sliding mode FTC architecture for multi-agent systems with disturbances was proposed in [125]. [126] Tackles the challenging task of monitoring interconnected systems based on predictive control. Several strategies; based on distinct fault tolerance techniques, have been developed and published to limit the impact of faults on LSSs, as illustrated in Table 1.

Intelligent methods, robust approaches, sliding mode, adaptive, $H_2/H\infty$, and multiple methods are among the most often used strategies to address this problem. These strategies have produced extremely good results but are difficult to compare since they approach issues and faults in different ways. Because they rely on the problem they are intended to solve, it is therefore hard to determine whether one method or algorithm is significantly superior to the other.

VI. CONCLUSIONS

Recently, efforts have been made conducted to increase the reliability of LSSs using FTC techniques. The basic goal of the FTC is to avoid unacceptable performance and hazard cases that cause a full shutdown, where the FTC systems would reduce the impact of control loop faults and ensure the system's safety and reliability. Decentralized control is still a major topic in systems theory due to the insatiable human drive to control more complex systems such as interconnected systems suffering from dimensionality, presence of interconnection between subsystems, faults, disturbances, uncertainty, and exogenous inputs. In this paper, several strategies were discussed based on developing decentralized FTC techniques to address the impact of faults on such systems. Additionally, this study aims to provide extensive information to researchers and developers on control and fault tolerance in large-scale applications. Some future works are suggested such: particularly for real-world applications, the issue of decentralized nonlinear LSSs impacted by numerous time delays and concurrent faults can be considered, and Uncertain nonlinear large-scale linked systems can be used to rethink the methods suggested in this paper, where the uncertainty may have an impact on the system in use.

TABLE I
COMPARISON BETWEEN DIFFERENT STRATEGIES

Analyzed Papers			Problems				FTCs Solving						
No.	Paper	Publication years	Actuator faults	Sensor faults	Actuator and sensor faults	Presence of disturbances	Adaptive method	$H_2/H\infty$	Sliding mode control	Intelligent method	Augmented backstepping	Predictiv e method	Multiple methods
1	[127]	2022	✓			✓	✓			✓			
2	[128]	2022	✓				✓						✓
3	[129]	2021	✓			✓				✓			✓
4	[125]	2019	✓			✓	✓		✓				
5	[111]	2018	✓				✓			✓			
6	[124]	2018	✓				✓						
7	[107]	2017	✓			✓				✓			✓
8	[109]	2017	✓				✓				✓		✓
9	[45]	2017	✓		✓		✓			✓			
10	[126]	2016	✓			✓						✓	
11	[123]	2015			✓			✓					
12	[108]	2014	✓							✓	✓		✓
13	[119]	2014		✓		✓						✓	
14	[121]	2013	✓						✓				
15	[120]	2012		✓			✓			✓			

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