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SURVEY

Self-Healing Control: Review, Framework, and Prospect

HUAQING LIANG AND XUNHE YIN
School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing 100044, China
Corresponding author: Xunhe Yin (xhyin@bjtu.edu.cn)

ABSTRACT The strong coupling between the components of a modern system and the increasing complexity of the system make the demand for intelligent control and maintenance of the system become higher and higher. Self-healing control extends the scope of intelligent control, which is an inevitable trend in the development of intelligence for automated systems. Self-healing technology has a wide range of applications, but its theoretical system has not yet been developed. First, the characteristics, functions, definitions, and theoretical framework of self-healing control are clarified by reviewing and summarizing the research status of self-healing technology and self-healing control in various fields. Second, the differences and relationships between self-healing control and control methods, such as fault-tolerant control and adaptive control, are analyzed and discussed. Finally, the development tendency of self-healing control is summarized. The research status of self-healing technology in related fields is analyzed and summarized, and the basic framework of self-healing control is extracted to lay the foundation for the theoretical exploration of self-healing control.

INDEX TERMS Self-healing control, fault diagnosis, fault tolerant, system recovery, system of systems.

I. INTRODUCTION

Complex systems often fail because of degradation during system operation. System downtime is unavoidable owing to these faults. A system failure is a slow process. If a fault can be detected, diagnosed, and controlled in the early stage, the adverse impact of fault propagation on the system can be avoided. Simultaneously, multiple faults may occur in the system, which requires fault identification and classification [1], [2], [3], [4]. With the increasing complexity of modern control systems, they are vulnerable to malicious attacks owing to the introduction of communication networks. Therefore, identifying faults and attacks is crucial. To address this problem, Autonomic Computing (AC) techniques and system self-maintenance have been introduced into complex systems.

The idea of a self-maintenance system gave birth to the AC, which has the purpose of transferring a part of the maintenance process to the system itself and achieving automation. The AC concept was initiated by IBM, who was inspired to use the structure of biological processes in computing systems [5]. The essence of AC is to reduce the system complexity through automation and provide the functions necessary for the self-management of computing systems through inherent self-adaptation. AC has good visions [6], and it defines the concept of self-management as comprising four basic policies: self-configuring, self-healing, self-optimizing, and self-protecting [7]. To achieve self-managing objectives, an Autonomic System (AS) must have the following self-* properties: self-awareness, self-situation, self-monitoring, and self-adjustment [8]. System self-management can be achieved through self-healing, which is a significant feature of self-management or AC. Self-healing is a basic strategy for implementing self-management in AS.

Self-healing is designed to solve system failures in automated maintenance tasks that fall under the AC category. This type of research is still in its infancy, although the application of such mechanisms to engineering problems has existed for nearly a century.

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Although increasing attention has been paid to the concept of self-healing, there are still some difficulties in its realization [9]. First, only a few studies have focused on self-healing. Second, there is a lot of work that is related to self-healing, but uses different terminology, which makes it difficult to distinguish self-healing from similar methods, the most typical of which is fault tolerance. For a long time, there has been no clear distinction between fault tolerance and self-healing, which hinders the progress of self-healing. It should be pointed out that fault tolerance is a much older research topic than self-healing and was initiated for hardware systems, whereas self-healing focuses more on software systems. This area has clearly inspired techniques for self-healing because of the precedence of fault tolerance. Some scholars treat self-healing as consisting of self-diagnosis and self-repair, whereas others have introduced the notion of assisted healing for systems that require human intervention during the healing process. The inclusion of human intervention significantly broadens the research field relevant to self-healing [5]. Self-healing technology has already been used in many fields, such as self-healing materials, self-healing robots, self-healing smart grids, mechanical self-healing, and aerospace self-healing.

Self-healing can be considered from three aspects: hardware, application, and system level [10], as shown in Fig. 1. From this figure, ''Algorithms'' in ''System Level'' are what we need to further explore.

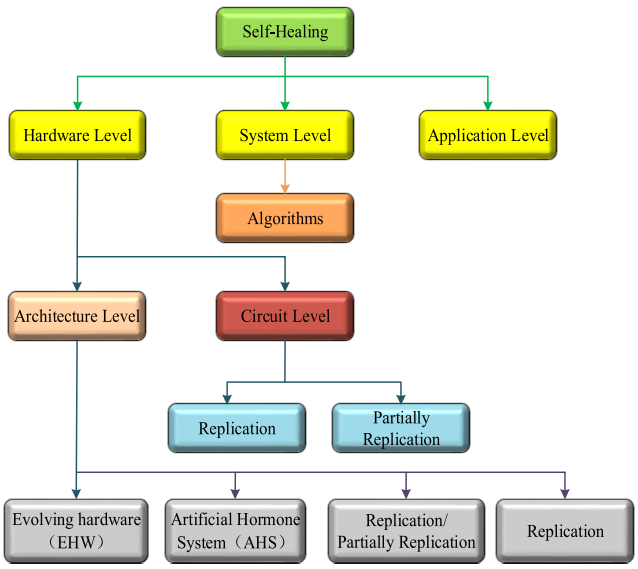


FIGURE 1. Self-healing classification diagram [10].

Self-healing technology is widely used in diverse fields. However, little research has been conducted on the theory of self-healing. Meanwhile, when referring to some references on self-healing control, the researchers only considered the realization methods of self-healing control from the corresponding field but did not provide the overall framework and basic characteristics of self-healing control from a theoretical perspective. Therefore, it is necessary to provide a framework and the basic characteristics of self-healing control, and then extend it to specific application fields. The major contributions of this study are as follows:

First, the applications of self-healing technology in several fields are summarized, and the characteristics of self-healing technologies in different fields are presented.

Second, by summarizing the characteristics of self-healing and combining the purposive behavior of the control system, the framework, definition, and working stage of the self-healing control system are presented.

Finally, the relationships and differences between self-healing control and various control methods are analyzed and discussed. It is pointed out that self-healing control is an extended method, which is developed on the basis of fault-tolerant control, adaptive control and other automatic control methods or intelligent control.

The remainder of this paper is organized as follows. In Section II, the applications and characteristics of self-healing technologies in diverse fields are presented and analyzed. In Section III, the characteristics of the bionic self-healing system are summarized and the features of the self-healing systems are presented. In Section IV, the definition and framework of the self-healing control system are proposed. The differences and relationships between self-healing control and similar control methods are compared. In Section V, research issues and prospects of self-healing control systems are presented. Finally, conclusions are drawn.

II. APPLICATIONS OF SELF-HEALING TECHNOLOGY

Applications of self-healing technology based on the self-healing principle began in the 1980s. For example, from the early application of self-healing materials to the widely used self-healing power grid, self-healing robots, and aerospace self-healing control, relatively mature self-healing technology has been well reflected in modern society for both citizens and the military. In this section, self-healing technologies in different fields are investigated. The characteristics of self-healing and self-healing mechanisms are summarized.

A. SELF-HEALING MATERIALS

Research on self-healing composite materials was reviewed, with an emphasis on capsule-based and vascular healing systems in [11]. Self-healing polymer materials were used as robot actuators in [12]. An innovative approach using self-healing (SH) polymers in flexible actuators based on a reversible Diels-Alder (DA) reaction was presented. To create an SH-compliant actuator, an SH mechanical fuse (SH-MF) was introduced as the weakest mechanical element. The fuse acts as an important sacrificial part and fails first if the actuator is subjected to overload, thereby protecting the other components of the actuator. In [13], machine learning was used to predict the self-healing efficiency of materials, and an online ensemble learning framework was presented as a whole system model for the optimization of predictive computational models. In [14], sodium silicate solutions stored

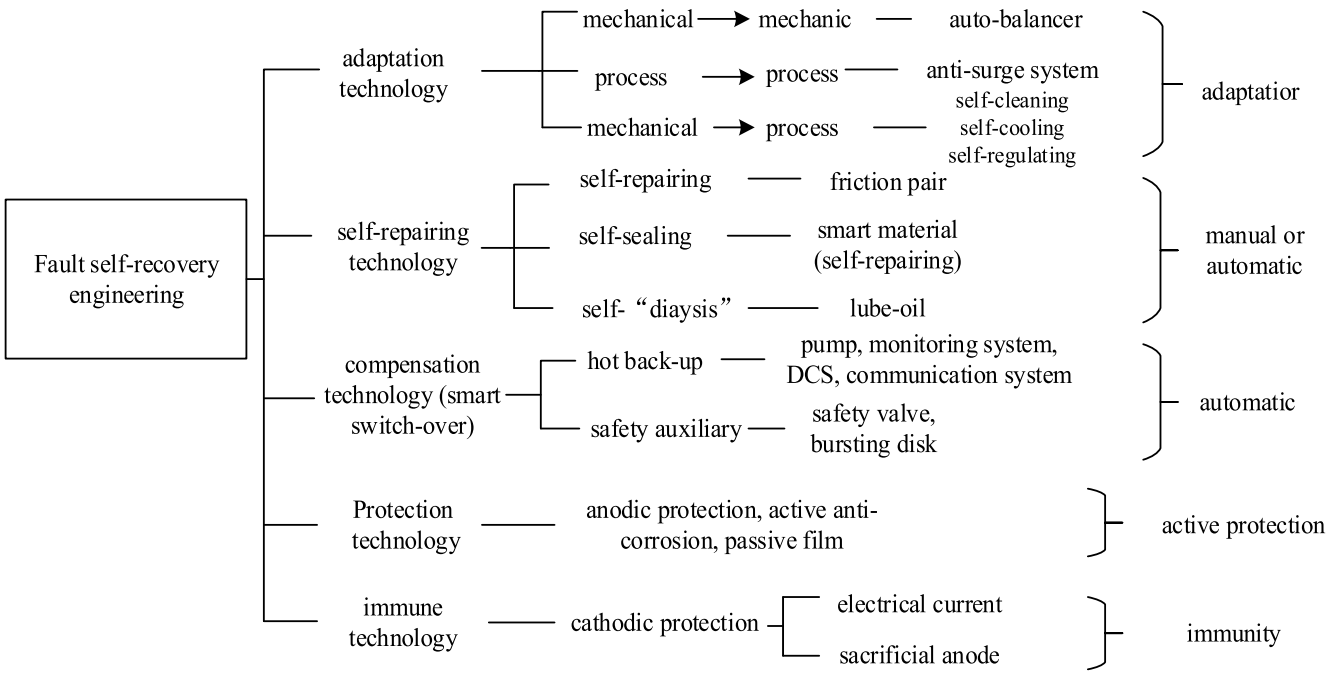


FIGURE 2. Classification of fault self-recovery engineering.

in polyurethane microcapsules were included in concrete. When concrete is damaged or cracked, the capsules can partially repair the crack by expanding the sodium silicate released when the crack breaks and reacts with the calcium hydroxide in the cement to form a calcium-silica-hydrate gel (C-S-H gel). From these articles, self-healing techniques in self-healing materials are realized mainly with physical or chemical properties.

B. SELF-HEALING ROBOTS

Robotic modules connect to each other through redundancy mechanisms. They exhibit a certain degree of self-adaptivity and self-organization. Self-healing is achieved through self-adaptivity and self-organization in [15]. In [16], space robots were individual identical mobile robots that collectively comprise a swarm robot. Individuals supervise and imitate each other and accomplish certain tasks through self-organization. In [17], a decentralized autonomous control algorithm using parallel processing with low-performance processors was developed to control hyper redundant manipulators for space robots. The system can position itself correctly, even if some joints are blocked. For self-healing robots, ① Self-healing methods on self-healing robot system include self-reconfigurable and redundancy technology. ② A self-repairing robot system may have redundant modules with the same function, and these modules are connected to each other through a certain mechanism. ③ The communication mechanism is important because it can make the system having the ability of self-adaptive and self-reorganized.

C. MECHANICAL SELF-HEALING

Self-healing control is widely used in the machinery industry. In [18], [19], and [20], the classification and main research fields of fault self-recovery engineering were presented, including adaptation technology, self-repairing technology, compensation technology, protection technology, and immune technology. The classification of the fault self-recovery engineering is shown in Fig. 2. In addition, they emphasized that the self-healing principle of equipment systems is not only an urgent need for engineering practice but is also an important topic to be studied in the future.

In [21], the proposed method monitored the stiffness of the oil film and identified the reason for the increase in axial displacement. By introducing the self-recovery mechanism of axial displacement, the rotor axial force is controlled online with axial displacement as the control objective to ensure a minimum oil film thickness in real time. In [22], self-healing was realized through self-monitoring, self-diagnosis, and active control during operation, which is an important direction of machine development in the advanced intelligence stage. In [23], an adaptive self-healing control method based on sliding mode variable structure fault-tolerant control was proposed to solve the problems of actuator failure and deviation in the stepless flow regulation system of a reciprocating compressor. In [24], the concept of artificial self-recovery was first proposed in the field of bionic mechanics. Artificial self-recovery is used to endow the machine with the self-recovery mechanism of humans and animals, to avoid and suppress failure during operation, and to realize self-recovery to ensure the essential health of the machine.

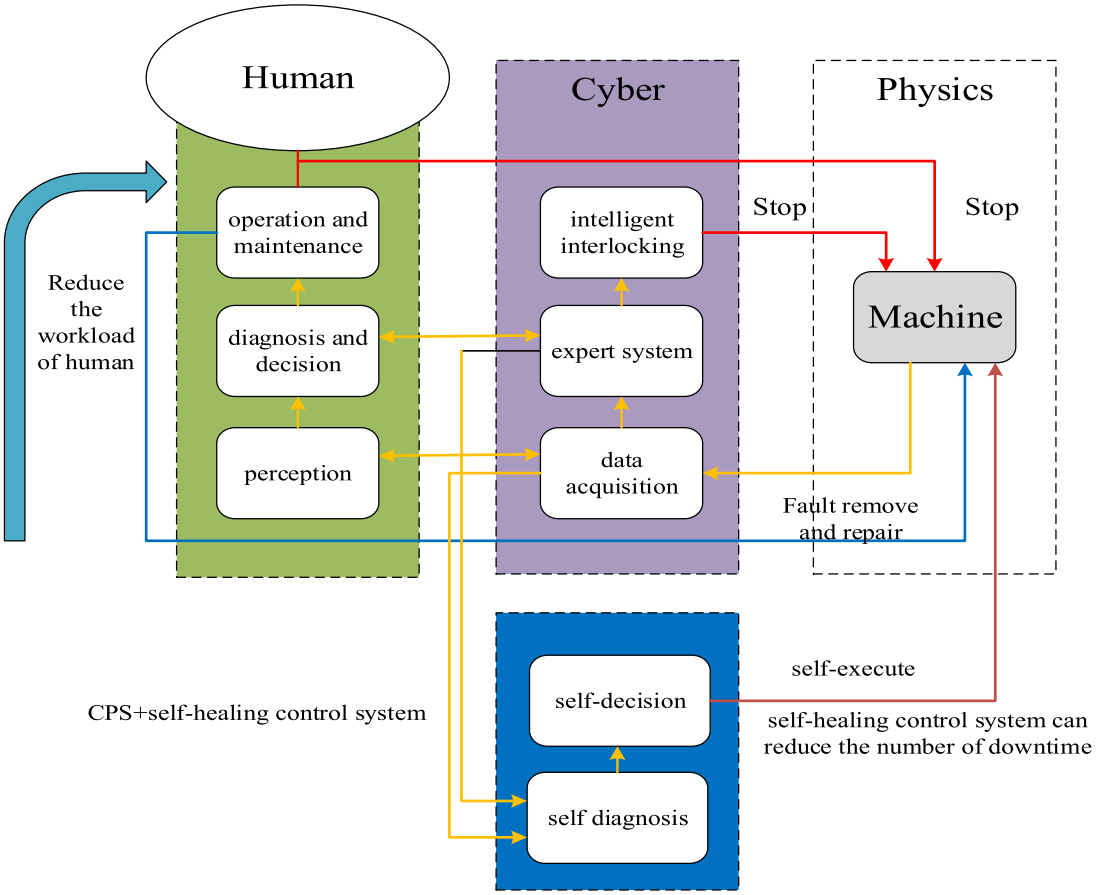


FIGURE 3. Machine cyber - Physical health care system.

A model of a machine fault self-healing control system was proposed. It also discusses a new field of engineering self-recovery theory. In [25], the definition of fault self-healing control was proposed: In the operation of the equipment system, real-time monitoring and analysis of possible fault conditions and early fault symptoms. The use of diagnosis and prediction, intelligent decision-making, and active control methods to ensure the equipment system does not have the conditions for failure or eliminate the fault in the bud, or in the stage of failure is not formed, to find it, intercept it, and make it disappear invisible. That is, a self-healing mechanism for fault prevention and elimination is established through control, so that the system can operate in a safe area and field by itself and maintain an orderly and stable state without falling to a natural equilibrium state.

In [26], the concept of artificial self-healing in machinery was proposed. Meanwhile, intelligent fault tracing and diagnosis of artificial self-healing have been developed based on artificial intelligence. With the application of computer networks in machine systems, an artificial self-healing system of a Cyber Physical System (CPS) was proposed. Seen in Fig. 3. In [27], future equipment will not only have the adaptability of parameter adjustment, but also have structural adaptability. Artificial self-healing can make future equipment and even manufacturing systems autonomous and healthy, and can enter the era of self-healing.

The characteristics of self-healing in mechanical can be summarized as: ① Mechanical self-healing mechanisms include self-healing control technology, self-repairing technology, compensation technology (intelligent switching), self-protection technology and immune technology. ② Past fault information is continuously collected and stored in a database by analyzing the causes of various faults. ③ Faults can be diagnosed and predicted accurately. At the same time, faults are eliminated during operation using intelligent decision and active control, so that the equipment will return to a normal state, and the faults of the mechanical system will self-heal.

D. SELF-HEALING SMART GRIDS

Applications of self-healing control in smart grids were introduced in [28], [29], [30], and [31]. In [32], the consistency between multi-agent in a smart grid was described. The most common self-healing method in distributed grids is the reconstruction strategy between the nodes. For example, the rapid recovery of distributed smart grids was investigated in [33] and [34]. In [33], an approach that determines new

configurations that are as local as possible to the faulty area increases the search space. New configurations were generated based on a heuristic method that relies on graph theory. An improved ant colony algorithm was proposed in [34]. In [35] and [36], the self-healing control method of a smart grid using a communication system and big data was studied. In [37], the key technology for self-healing control was reviewed, and an insight into the role of self-healing in distribution systems was provided. Subsequently, the challenges and opportunities in the prospect of utilities were studied, along with the proposed architecture, a control strategy for a self-healing control system including fault detection, fault localization, and faulted area isolation. In [38], a new real-time adaptive defence method for isolated islands was proposed. Indices of self-healing were proposed in [29] and [39]. In [40], a design method for an agent-based self-healing protection system was proposed, and an expert system based on graph theory that integrates monitoring and data acquisition was developed. Each relay protection agent was assigned to a specific region according to the topological structure of the system. According to their application in smart grids, ① Self-healing control after failure can be roughly summarized by three methods: mathematical programming methods, heuristic search methods, and artificial intelligence methods. ② The methods for smart grids to achieve self-healing are reorganization between nodes in the network topology, reconfiguration of the distribution network structure based on graph theory, fault detection, fault location, and fault isolation technologies. ③ Self-healing in a smart grid is achieved through unified cooperation with the self-awareness, self-diagnosis, self-decision, and self-recovery modules.

E. AEROSPACE SELF-HEALING

In [41], China's 12th Five-Year Plan for Science and Technology Development identified major scientific issues in the aerospace industry and promoted research on fault diagnosis and fault-tolerant control. In [42] and [43], self-healing control comprised of fault diagnosis and fault-tolerant control. In [42], the model reference approach was used to obtain a tracking error dynamic equation by integrating fault estimation and fault-tolerant control units in a dynamic system. An augmented error system is constructed by considering the fault as an auxiliary vector, and a fault estimator/controller is designed based on the augmented error system. In [43], self-healing control systems are a class of control architectures and design methodologies characterized by their ability to counteract faults actively and help maintain a certain level of control performance. In [44], a self-healing control framework was proposed for actuator stuck faults in unmanned helicopters. The framework comprises an active fault-tolerant control system and a reference redesign. In addition, in [45], the idea of combining fault detection isolation with fault tolerance control, and fault estimation with fault tolerance control was proposed. In [46], a sliding mode and dynamic surface-based fault-tolerant method was proposed for controlling a faulty HFV with mixed aerodynamic surfaces and RCS jets. In [47], a new method was proposed for detecting, estimating, and self-repairing intermittent faults of a reentry hypersonic flight vehicle under complex interference conditions. In [48], a self-repair strategy for UAV based on neural network inverse control (NNIC) was realized by using the functional redundancy of the flight control system. Accordingly, ① Self-healing control methods are primarily considered from the controller perspective. ② Self-healing control is an intelligent method that monitors a system in real-time and adopts active control strategies. ③ Integrating fault-tolerant control and real-time monitoring modules into a large module, the controller is reconfigured online in real time, which highlights the powerful role of the monitoring system. ④ The self-healing controller is designed based on adaptive control, fault-tolerant control, sliding mode control, and immune control.

F. SELF-HEALING SENSOR NETWORKS

Self-healing has been widely used in sensor networks. In [49], industrial wireless sensor networks (IWSN) played a vital role in creating a highly reliable and self-healing industrial system that responds rapidly to real-time events with appropriate actions. In [50], a self-healing scheme based on single flow-controlled mobility within a cluster to achieve a trade-off between self-healing and energy consumption in mobile unattended wireless sensor networks (UWSNs) was proposed. Thus, UWSNs can exploit controlled sensor mobility to enhance network capability in terms of self-healing and reduce communication-related energy consumption. In [51], a cooperative hybrid self-healing random distributed scheme and a new mechanism to enhance the confidentiality of data collected by UWSNs were proposed. The proposed scheme employed both proactive and reactive peers to ensure backward secrecy and data reliability. Meanwhile, in [52], [53], and [55], self-healing of UWSNs was studied. In addition, in [57], self-healing algorithms were provided as an optimization to border coverage algorithms that allow the sensor network to adaptively reconfigure and repair itself to improve its performance. In [59], a novel distributed algorithm called neighbor intervention by the farthest point repairs coverage holes using mobile sensor nodes in the immediate vicinity. Participating nodes collaborate to approximate the area of the hole and then consider their coverage redundancy, residual energy, and moving distance to select a suitable replacement.

Moreover, when UWSNs were attacked, in [52], the problem of cooperative self-repairing in UWSNs was studied, and various techniques were proposed to restore the security of UWSNs after being attacked. In [55] and [58], the self-healing strategy of UWSNs in the face of invasion and attack is discussed. The life span of UWSNs can be extended by self-healing routing in [61]. It can be found that, ① Sensor networks belong to self-organizing network, which have the ability of acquisition, analysis and control. ② Self-healing sensor networks realize self-healing by reconstructing the

nodes in self-organizing sensor networks, as reported in [54], [56], [57], and [60].

G. SELF-HEALING CONTROL IN OTHER FIELDS

1) SELF-HEALING BASED ON MULTI-AGENT SYSTEM (MAS)

In [62], a control and protection framework based on multi-agent system (MAS) was proposed, in which the situational awareness of zone agents plays an important role. Primary protection is designed to locate and isolate faults based on peer-to-peer communication. Fault-tolerant mechanisms, including self-inspection and backup protection, have been developed to cope with the malfunctions of individual MAS and local communication failures. In [63], based on the multistage characteristics of self-healing control in smart distribution systems, an integrated multi-stage self-healing strategy based on MAS was proposed, in which the complex self-healing problem was decomposed into phased sub-problems. In [64], a swarm intelligence coverage and self-healing method based on the Self-Organizing Network Model (SONM) and a potential function were proposed for MAS. Based on this, a multi-agent coverage and self-healing control law was devised, and a potential function was designed to realize collision avoidance, coverage, and self-healing control for the MAS. Self-healing control based on MAS is primarily realized through the recombination of topologies between agents.

2) SELF-HEALING IN INDUSTRIAL PROCESS

In the smelting process of fused magnesium furnaces (FMFs), owing to the change in the raw material granule size and impurity constituents, the smelting current fluctuates, which leads to an abnormal situation and deterioration of the performance of the control system. In [65], a data-driven abnormal condition identification and self-healing control system was proposed by analyzing the characteristics of different working conditions. The abnormal condition was identified using rule-based reasoning, and self-healing control was achieved using case-based reasoning. In [66], abnormal condition identification and self-healing control of fused magnesium furnaces based on multisource information fusion were presented. A Bayesian network for identifying abnormal conditions was established by fusing multisource information. Self-healing control measures are obtained based on the identification of abnormal conditions. Data-driven abnormal condition diagnosis and self-healing control methods were reviewed in [67]. In addition, future research directions and recent progress on the topic of operation monitoring and self-optimization of industrial processes are discussed, including: 1) data-driven multi-level comprehensive monitoring of decisions, cooperative control, and base-level control; 2) multi-source dynamic information-based abnormal situation diagnosis that combines first principles, process data, and expert knowledge; and 3) cooperative self-healing control, which combines expert knowledge and control strategy.

In [68], for the hot strip rolling process, a data-driven integrated framework for monitoring and self-recovery control was developed based on the monitoring and control requirements for the dynamic performance of the control system and the operational performance of the production conditions. However, most of the previous research studies focused on the implementation of active/passive fault-tolerant control to solve the fault of a single loop or single equipment in the production process, and paid relatively little attention to the fault-tolerant control technology of system-level faults that can affect product quality and system performance. In [69], the authors addressed control performance monitoring (CPM) and degradation recovery in automatic control systems.

In industrial processes, self-healing control is realized through logical reasoning based on the identification of abnormal conditions.

3) OTHERS

In [70], the self-healing control problem for a large launch vehicle (LLV) with system uncertainties, external disturbances, and actuator faults was investigated. An extended state observer (ESO) was designed to estimate the disturbances and fault information. An integral terminal sliding-mode fault-tolerant control scheme was proposed for an attitude faulty system. By using the adaptive dynamic programming (ADP) technique, supplementary control with an actor-critic structure was employed to improve the system tracking performance. In [71], a hybrid control block diagram with a diagnosis-free self-healing scheme for a dual three-phase permanent magnet synchronous motor (PMSM) was presented. In the torque subspace, a typical PI control is used to realize an accurate closed-loop control of the d-q current. In the harmonic subspace, deadbeat predictive current control was adopted to achieve effective tracking for both DC and sinusoidal current references under normal and faulty operations. The self-healing dilemmas of distributed systems were presented in [72]. Faults in distributed systems can be caused by system faults, software faults, security attacks, or any other type of error that prevents failing nodes from accessing healthy nodes. In [73], a battery control system with a fast dynamic response was shown to mitigate the impact of pulsed power loads (PPLs) on the voltage and frequency of navy ship power systems (NSPS). A self-healing control scheme based on the feasible range of power transfer and the voltage profile of the AC link inductance is presented in this paper. The proposed method can verify and automatically correct the predicted current and phase shift of the DAB converter interface in a battery system.

Self-healing ability is applied to many fields because its powerful self-recovery function brings convenience to all walks of life. The widespread use of self-healing technology has prompted researchers to explore it from various perspectives. However, so far, the application research of self-healing technology is still restricted to a certain professional field,

and research on self-healing theory is still in its infancy; namely, the study of self-healing theory lags far behind its application. Self-healing is a natural process in which self-healing technology has developed to a certain stage in various fields. The reason for the mismatch between the application of self-healing technology and the development of self-healing theory is that there are certain differences between various disciplines and fields, and it takes a certain amount of time to break down the barriers between them. Therefore, its application lags the development of this theory.

To further improve self-healing theory, it is necessary to analyze the definition of self-healing from a biological perspective, thus laying a foundation for the establishment of self-healing system theory.

III. BIONIC SELF-HEALING AND SELF-HEALING SYSTEM

A. BIOLOGICAL SELF-HEALING SYSTEM

Self-healing is a stable and balanced self-recovery mechanism that inhibits self-destruction or self-attenuation owing to a self-healing system. The self-healing system is a synergistic dynamic system that stores, supplements, and mobilizes self-healing ability to maintain a healthy body. From a medical perspective, self-healing systems are inseparable and inalienable. Meanwhile, it is also a functional and energetic intelligent system that permeates large numbers of subsystems in an organism [74]. Various subsystems of self-healing systems are widely distributed in all corners of the body and have the abilities of self-defense, self-healing, self-maintenance, regeneration, and distributed management. Generally, distributed subsystems with self-healing functions communicate with each other.

The bionic self-healing system was fabricated using a biological self-healing system. The engineering field includes the nervous system, information system, immune system, repair system and stress system [18]:

Nervous System: This is a diagnosis prediction and intelligent decision system and a sensor-signal processing system.

Information System: It influences the energy and information input/output of the controlled objective by transmitting information.

Immune System: It resists external interference.

Repair System: It has the ability of healing and regeneration.

Stress Systems: It is sensitive to the changes and deviations.

These are the five subsystems of the bionic self-healing system. Although they differ from the perspective of subsystem functions, they have consistent goals, and cooperation between them is required to maintain the health and stability of the system. Consequently, an independent and unified relationship exists between the two variables. Fig. 4 shows the relationship between the five subsystems, which indicates that the bionic self-healing system is a complex system with dynamic coordination.

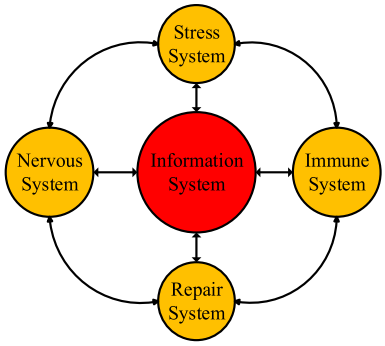


FIGURE 4. Composition of bionic self-healing system.

B. SELF-HEALING SYSTEM

The earliest research paper on self-healing control can be traced back to 1968, when the concept of self-healing control was put forward by Briley in the computer field. Self-healing control is a self-repairing technology for electronic computers that does not require systematic replication [75]. In subsequent research on self-healing control, since most scholars regard self-healing as an attribute of the system, the term ''self-healing control'' is not widely used, but ''self-healing system'' is used to represent a system with self-healing properties. Therefore, theoretical studies on self-healing control are limited. Although self-healing systems and self-healing control are not exactly the same concept, the fusion application of self-healing systems and self-healing control systems has gradually formed with the rapid development of information technology processing and the convenience brought about by multi-disciplinary science.

In [76], the survey was introduced with an outline of the origins of self-healing. The fundamental principles of self-healing systems were identified based on the principles of autonomic computing and research on self-adapting systems. At the same time, the system is defined as ''...a self-healing system should recover from the abnormal (or ''unhealthy'') state and return to the normative (''healthy'') state, and function as it was prior to disruption.'' Moreover, the relations and properties of self-healing research are presented. Seen in Fig. 5. In [77], a taxonomy for describing the problem space for self-healing systems, including fault models, system responses, system completeness, and design context, was proposed. All of these studies laid the foundation for the formation and development of self-healing control.

In [10] and [78], it was shown that a system with self-healing properties has three states: normal state, degraded state, and broken state. The normal state is considered to be a healthy state, whereas the degraded and broken states are unhealthy. A system does not break down immediately but deteriorates over time (fault occurrence is a gradual process). Therefore, the degraded state (fuzzy state) is the distinction between normal and broken states. As shown in Fig. 6, the system transitions from a normal state to a degraded state when faults begin to occur.

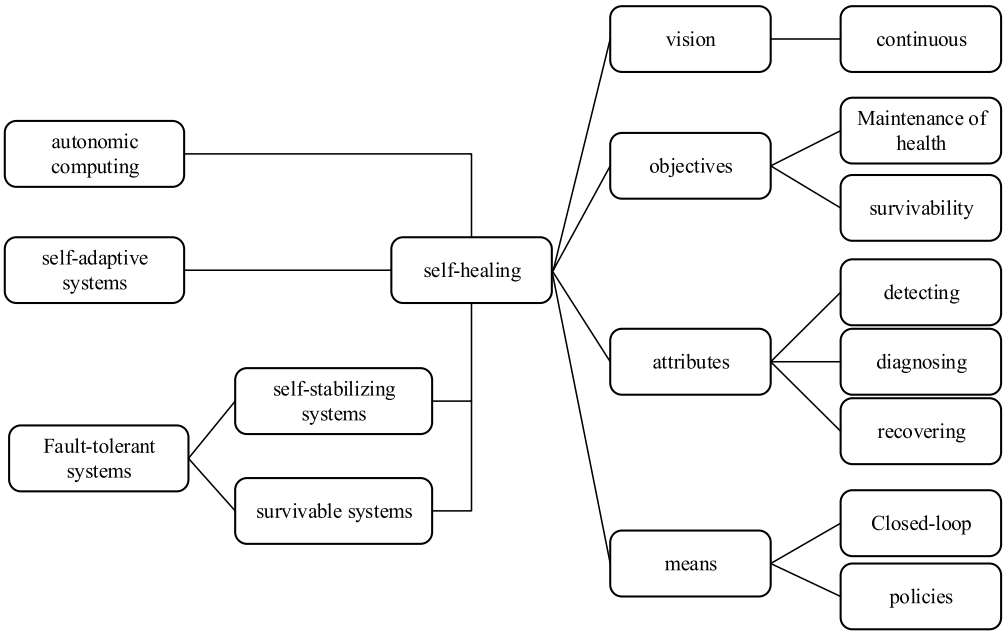


FIGURE 5. Relations and properties of self-healing research.

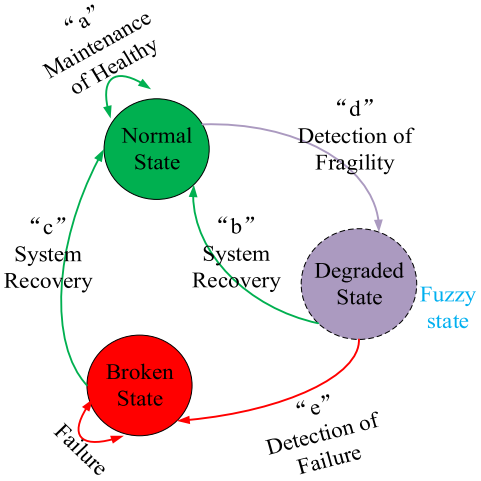


FIGURE 6. State diagram of self-healing system [1], [78].

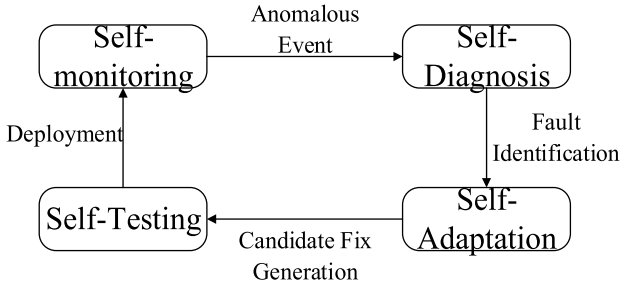


FIGURE 7. Closed loop structure of self-healing system [10], [79].

Fig. 6 shows the state diagram of the self-healing system. (1) When in a normal state, the system will be maintained in this healthy state continually by optimizing itself–process “a”. If fragility is detected, the system state switches to a degraded state –process “d”. (2) When in a degraded state, if fragility has been recovered, the system returns to the normal state–process “b”. Otherwise, if the system continues to deteriorate beyond the threshold of degrade state, it goes to a broken state–process “e”. (3) When in a broken state, the system continues to attempt to fix the fault. After recovering, the system returns to the normal state–process “c”. From this diagram, processes “a”, “b”, and “c” are self-healing processes. The detection processes “d” and “e” are essential.

The self-healing feedback structure consists of four stages: self-monitoring, self-diagnosis, self-adaptation, and self-testing [10], [79], as shown in Fig. 7. The system was monitored using a self-monitoring stage, which provided an indication of anomalous events. Subsequently, the system switches to the self-diagnosis stage and the fault is identified. Meanwhile, fault information was extracted with respect to the cause of the problem, symptoms, and impact on the system. Once identified, the system will try to adapt by generating candidate fixes, which are tested to find the best expected state.

IV. SELF-HEALING CONTROL SYSTEM

A. SELF-HEALING CONTROL SYTEM

Some abilities are embraced in self-healing systems such as self-monitoring, self-diagnosis, and self-repair, which are manifestations of system intelligence that enable self-healing without human participation. Considering the ultimate goal of self-healing systems, intelligent systems with self-healing capabilities are more suitable for the current development trends of intelligence. Controlled self-healing systems are an advanced development goal for artificial intelligence (AI).

The initiative is brought to an intelligent control system so that the stability and reliability of the system can be realized by adding a control algorithm and adjusting the feedback information [80].

Self-healing is an old concept, but self-healing control is a new field. The establishment of a self-healing control system is based on a self-healing system and a control idea. In Section III-A, it is considered that a bionic self-healing system consists of several subsystems that work together to make the organism healthy and stable. In Section III-B, it is pointed out that in Fig. 6 and Fig. 7, self-monitoring, self-diagnosis, self-decision, and self-repairing are required in the self-healing system. In addition, from the ''self-healing attributes (also shown in Table 5)'' of self-healing technology in many fields in Section II, it is found that self-healing control also has the following general characteristics: without human intervention, fault detection and diagnosis, prevention/suppression/elimination of faults, and knowledge support.

Here, the definition of self-healing control system is given. A self-healing control system is a complex feedback control system composed of multiple subsystems with self-monitoring, self-diagnosis, self-decision, and self-repairing abilities, of which the self-monitoring subsystem is the most basic and necessary. The purpose of self-healing control is that when any component or subsystem fails, the potential fault of the system can be prevented, and the existing fault can be suppressed or eliminated using an appropriate control strategy to guarantee system sustainability and stability are guaranteed. The self-healing control process includes self-optimization, self-diagnosis, self-decision, and self-repair stages (see Fig. 8), which exhibit the characteristics of real-time optimization, fault suppression, fault isolation, and fault repair.

Self-optimization is necessary for self-healing control in the proposed self-healing control process. In the self-healing control process, when no anomaly is detected, the system is considered to be in a normal state. In the normal state, the system must optimize itself to ensure system stability. Therefore, self-optimization is necessary to maintain a stable system and other performances when in a normal state. Self-optimization is a step in self-healing control and is also an optimization control. Therefore, when implementing this control, it is necessary to refer to normal control law design ideas, including the state observer design and system stability, etc. Methods for implementing self-optimization include H_∞ and other robust control techniques, linear matrix inequality (LMI), model predictive control (MPC), and linear quadratic (LQ), etc.

Remark 1: For fault-tolerant control, decisions must be made after fault diagnosis. However, self-healing control is not exactly the same as fault-tolerant control. In addition to focusing on fault results, self-healing control focuses on the control process of the system. Because the occurrence of system failure is not instantaneous, it is a transition process. Self-healing control can monitor the system status in real time. When signs of system failure are detected during the transition process from the normal state to the fault state, certain adaptive measures can be taken to suppress the propagation of faults. Adaptive measures are considered preventive behaviors before the system makes a decision.

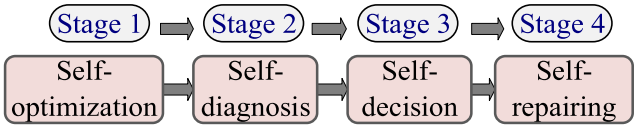
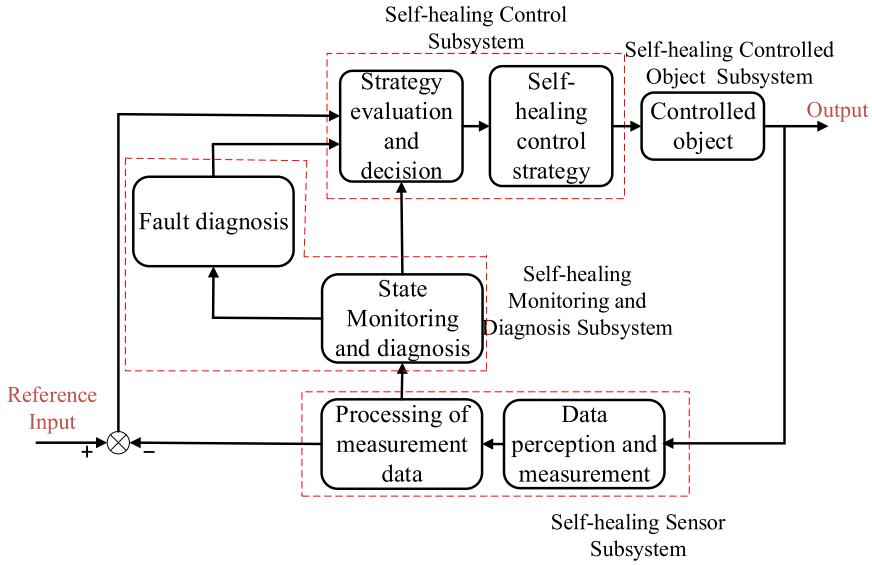
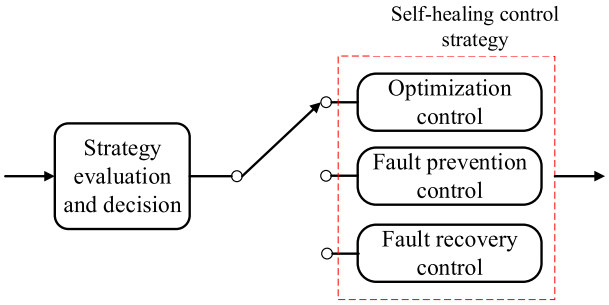


FIGURE 8. Four stages in self-healing control.

It is worth mentioning that self-healing control is not an absolutely new approach, it is a more intelligent system that integrates many self-* properties. The structure of the self-healing control framework is presented in Fig. 9 (a) based on its definition, abilities, functions, and working stages. This figure includes a self-healing controlled object subsystem, a self-healing sensor subsystem, a self-healing monitoring and diagnosis subsystem, and a self-healing control subsystem. (1) Physical objects that must be controlled are typically contained in a self-healing controlled object subsystem. (2) The ''Data perception and measurement'' module and the ''Processing of the measurement data'' module are included in the self-healing sensor subsystem. Effective data and information support are provided for the realization of a self-healing control system. (3) The self-healing monitoring and diagnosis subsystem contains two modules: ''state monitoring and diagnosis'' module, and ''fault diagnosis'' module. The evaluation of system state and the estimation of the risk level of potential failure are obtained from ''state monitoring and diagnosis'' module. Fault information is obtained from the fault diagnosis module by analyzing the fault status. (4) The self-healing control subsystem consists of the ''strategy evaluation and decision'' module and ''self-healing control strategy'' module. The self-healing control strategy module includes real-time optimization control, fault prevention control, fault recovery control, and other self-healing control strategies. This is illustrated in Fig. 9 (b). According to the evaluation of the fault risk level, an appropriate self-healing control strategy is selected based on the evaluation and decision. The self-healing control subsystem, which has the ability to store and update existing self-healing control strategies, has an adaptive repair function. Under the framework of a self-healing control system, it is observed that the self-healing control system is an intelligent control system with active recognition, judgment, and decision. Therefore, the realization of self-healing control depends on high-precision monitoring equipment, complete fault-diagnosis technology, and advanced control methods. Research on the self-healing control theory is still in its infancy. The development of advanced control methods and



(a) The structure of self-healing control framework



(b) Self-healing control subsystem

FIGURE 9. (a). The structure of self-healing control framework (b). Self-healing control subsystem.

information processing technologies will lay the foundation for self-healing control.

For the fault problem of traditional control systems, from the transition process of fault occurrence, fault-tolerant control measures after fault occurrence and self-healing control during the process of fault occurrence are considered. When the system changes from a normal state to a fault state, the deterioration and propagation of the fault can be prevented by fault suppression control, such that the system fault can be suppressed even when the fault state is not completely reached.

B. COMPARISION AND ANALYSIS FOR SELF-HEALING CONTROL AND SIMILAR CONTROL METHODS

1) SELF-HEALING CONTROL AND FAULT TOLERANT CONTROL

Fault-tolerant control and fault-tolerant technologies are involved in self-healing control. However, studies on the relationship between self-healing and fault-tolerant control are scarce.

Self-healing control means that when the system faces faults, it has a self-healing ability by stimulating the self-healing mechanism without human intervention. A self-healing control system is a complex feedback control system composed of multiple subsystems with self-monitoring, self-diagnosis, self-decision, and self-repairing abilities. The purpose of self-healing control is that when any component or subsystem fails, the potential fault of the system can be prevented, and the existing fault can be suppressed or eliminated using an appropriate control strategy to guarantee system sustainability and stability. Fault- tolerance control is to make the system have the ability to tolerate faults. In the case of a system failure, the basic function of the system can still be realized. Self-healing control emphasizes prevention strategies before failure, and self-recovery strategies after failure. However, fault-tolerant control mainly emphasizes the ability of the system to tolerate faults and requires the system to work normally when faults occur. In addition, redundant systems have certain relationships and differences with fault-tolerant control and self-healing control.

TABLE 1. Self-healing control and fault tolerant control.

Technology fields	Fault-tolerant control	Self-healing control
Concept	Fault tolerant control is to make the system have the ability of fault tolerance.	Self-healing control is to make the system have the ability of fault recovery with no human intervention.
Objects	The system that fails.	The system that fails and requires self-recovery.
Feedback information	The deviation of the system's output from the expected value.	The deviation of the system's output from the expected value and the state of system.
Characteristics	(1) For passive tolerant control, emphasizing the coexistence of the system and the fault. (2) For active tolerant control, emphasizing fault detecting, fault type diagnosing, fault isolation, and fault recovery.	(1) Self-monitoring, self-diagnosis, self-decision and self-repairing. (2) Prevention, suppression and elimination for system fault. (3) The recovery strategy is considered at the system level.
Target	System works in normal operation with fault tolerance.	Prevents before failure and recovers after failure through intelligent decision-making.
System	System is always working during the whole operation.	System is working in normal control when no faults occur. When faults occur, the self-healing mechanism is activated to take self-healing control.
Self-healing degrees	Low level	High level

A redundant system is designed with two or more sets of identical independent backup configurations to enhance system reliability. When the system fails, the redundant components step in and take over the work of the faulty component, thereby reducing the system failure time. Because a redundant system needs to configure the corresponding components repeatedly, it has a high cost. At the same time, the measures to deal with uncertainty and failure are relatively simple. Therefore, *the self-healing degree of redundant system is primary*.

Fault-tolerant control can adopt more flexible measures than redundant systems when dealing with system faults. In addition to hardware redundancy measures, control methods with fault tolerance can be used to achieve this goal. *The purpose of fault-tolerant control does not emphasize fault recovery, but it does have a certain recovery function, so the self-healing degree of fault-tolerant control is intermediate.*

Self-healing control implements a corresponding strategy to the abnormal state of the system on the premise that the system has the ability to tolerate faults, so that the system has the ability to prevent, suppress, and eliminate faults. By monitoring the diagnosis, intelligent decisions, and advanced control, self-healing control can prevent faults and eliminate repairable faults during system operation. Compared to redundant systems and fault-tolerant control, self-healing control makes more comprehensive use of the state information of the system during operation and has an intelligent decision-making mode. *Self-healing control emphasizes system-level recovery after a failure. The self-healing degree of self-healing control is higher.*

Self-healing of the system can be realized through redundant systems, fault-tolerant control, and self-healing control. However, their self-healing degrees are different, and the degree of self-healing is determined by the system goals.

Fault-tolerant control belongs to the cybernetics research category. It is a control method that aims to achieve basic performance under the condition of failure. However, self-healing control is not the same. It not only needs to ensure the basic performance of the system, but also needs to restore other indexes to the normal state by self-recovery. Therefore, self-healing control can be regarded as further extension and expansion of fault-tolerant control. In addition, from the perspective of the realization method of self-healing control, it can be accomplished by fault-tolerant control with active properties, which further reflects that the research content of self-healing control is wider than that of fault-tolerant control. A comparison between self-healing control and fault-tolerant control is presented in Table 1.

Remark 2: Compare the difference between self-healing control and some classic actuator redundancy fault tolerance: The concept of fault-tolerant control originates from the computer field, which is generally defined as follows: when the actuator, sensor, or component failure occurs in the system, the control system can still ensure its own safe operation through fault-tolerant control adjustment, and meets certain performance indicators and requirements. Most of these classical fault-tolerant controls focus on the implementation of active or passive fault-tolerant control to solve the fault of a single component or device.

In self-healing control for the failure of the system, the goal of solving the problem is to consider the self-recovery function from the whole system level (not only referring to the failure of a single part). Meanwhile, it can not only realize

TABLE 2. Self-healing control and adaptive control.

Technology fields	Adaptive control	Self-healing control
Concepts	Adaptive control can adjusts system parameters automatically to achieve optimal control.	Self-healing control can adjust parameters and structures according to self-healing mechanism with unmanned intervention.
Bionic principle	Organisms' ability of adaptiveness.	Self-healing ability of an organism's self-healing system.
Objects	A control system with uncertainty	A control system with faults.
Characteristics	Identification of system structure, parameters, performance indicators, etc.	The system will be self-healing by activating the self-healing mechanism.
Target	When the environment changes, adaptive control can be realized by adjusting the parameters.	When the environment changes, self-healing control can be realized by adjusting the parameters and structures.
System	The system is always working during the whole operation.	System is working in normal control when no faults occur. When faults occur, When faults occur, the self-healing mechanism is activated to take self-healing control.

TABLE 3. Self-healing control and resilient control.

Technology fields	Resilient Control	Self-healing Control
Concepts	The controller adapts to the system' internal and external environment changes.	Self-healing control can adjust parameters and structures according to self-healing mechanism with unmanned intervention.
Objects	The uncertainty of system or the system attacked.	The system that needs recovery when fault occurs or attacked.
Characteristics	Controller is often designed off-line.	Controller is often designed online.
Targets	System performance index will be optimal by resilient controller when there are uncertainties.	The reconfiguration of controller online will be realized by self-adjustment when facing uncertainty.
System	The system is always working during the whole operation.	System is working in normal control when no faults occur. When faults occur, When faults occur, the self-healing mechanism is activated to take self-healing control.

fault tolerance and recovery but also ensure the performance index of the system.

Remark 3: Self-healing control in multi-agent system is essentially the same as that in normal control system. The difference is that in multi-agent system, real-time interaction of information is required between agents. Therefore, self-healing control also needs to be considered from the topological structure of the whole system.

2) SELF-HEALING CONTROL AND ADAPTIVE CONTROL

An adaptive control system automatically adjusts parameters to achieve optimal control as the operating environment changes without human intervention. It mimics the adaptive ability of living organisms, mainly because of the uncertainty of the system (including the uncertainty of the mathematical model of the controlled object and its environment). Adaptive control obtains adaptive ability through identification (including identification of the system structure, parameters, and performance indicators). As the parameters of the controller are constantly adjusted with changes in the object characteristics and environment, the controller has a certain ''self-adaptive'' ability. For a conventional control system, the controller only has the ability to restrain the internal characteristics and the influence of external disturbances, but it does not have the ability to adapt itself. Therefore, adaptive control is very effective for control systems whose object or disturbance characteristics vary significantly and require high performance.

Self-healing control is derived from the self-healing ability of organisms and is mainly aimed at self-healing control of the system when faults occur. In self-healing control systems, the parameters and structure of the system are primarily regulated based on the self-healing mechanism. Compared with conventional control, self-healing control not only has the ability to suppress the uncertainty of the model and environment but also has the ability to self-recover the system in the case of failure. Therefore, a self-healing controller can be

TABLE 4. Self-healing control and immune control.

Technology fields	Immune Control	Self-healing Control
Concepts	Immune control is a self-adjusting, self-organizing and self-learning immune feedback controller based on immune feedback and learning mechanism.	The system realizes self-healing control by adjusting parameters and structure according to self-healing mechanism with unmanned intervention. Self-healing control is to make the system have the ability of fault recovery with no human intervention.
Bionic principle	Immune feedback mechanism.	Self-healing mechanism.
Objects	The disturbance of internal or external in system.	The system that fails.
Characteristics	(1) Distributed adaptive system. (2) Using learning, memory, and association to identify and classify tasks. Immune defense, immune self-stabilization, immune surveillance.	(1) Distributed self-healing system. (2) Self-monitoring, self-diagnosis, self-decision, and self-repairing.
Targets	When there are internal or external disturbance, immune control make the system to achieve self-stabilization through surveillance and defense.	When a system fails, self-healing control can make the system run normally and maintain its performance.
System	When there are disturbances, immune control is activated.	System is working in normal control when no faults occur. When faults occur, When faults occur, the self-healing mechanism is activated to take self-healing control.

regarded as a combination of a conventional controller and a controller with self-healing abilities. However, considering a control system with adaptive ability from the perspective of system self-recovery, it can be concluded that adaptive control belongs to the self-healing control research category.

Further development of adaptive control is towards ''self-learning'' and ''intelligent control'' systems. In addition to general adaptive functions, these systems also have a large memory, pattern recognition, and a variety of advanced decision functions with intelligence. Such systems can remember past experiences and lessons of the system, recognize what has happened before, and gradually improve their adaptive actions based on past experiences. Self-healing control involves self-learning and self-decision. Self-healing control systems can remember past experiences and lessons, identify the situation that has occurred, and implement self-healing control based on past experience. Therefore, self-healing control can be regarded as a further development of adaptive control. See Table 2 for a detailed comparison of self-healing control and adaptive control.

3) SELF-HEALING CONTROL AND RESILIENT CONTROL

The design of the resilient controller ensures that it has a certain resilient range. Uncertainty is considered, in addition to the controller robustness of the system. In other words, the tolerance range of the controller in the designed controller is considered. Typically, the controller should be tolerant when the system is attacked. Although resilient control only maintains the degree of tolerance and does not reflect the function of automatic recovery, but from the realization goal of the system, it makes the system capable of self-healing. The self-healing ability of resilient control is realized by designing the resilient range of the controller.

Compared with the resilient control, the self-recovery characteristic is the most obvious in the self-healing control. When the system is faulty or attacked, self-healing control enables it to achieve self-healing through self-detection, self-decision, and self-recovery. The concepts, characteristics, and targets of the two control methods are compared in Table 3.

4) SELF-HEALING CONTROL AND IMMUNE CONTROL

In immunobiology, immunity is the ability of the body's immune system to effectively prevent diseases and to recover quickly. Self-healing is not only reflected in the ability to prevent disease but also to repair and rebuild itself after the organs are damaged. Immunity is more about defending against ''external threats,'' whereas self-healing is more about accelerating the body's healing rate. Immunity focuses on external factors, whereas self-healing focuses on internal ones. Both play their own roles, but are also related to each other. The stronger the self-healing, the stronger is the immunity.

Referring to the concepts of immune system and immunity, the concept of artificial immunity was proposed in engineering by Farmer et al. in 1986, and artificial immunity came into being. The control system is an application of artificial immunity; therefore, immune control has emerged, and there is an immune dynamic control system.

TABLE 5. Comparison of some similar control methods.

Attributes \ Control method	Self-healing control	Fault-tolerant control		Adaptive control	Resilient control	Immune control
		Passive fault-tolerant control	Active fault-tolerant control			
Parameter adjustment	√	N	√	√	N	P
Structure adjustment	√	N	√	N	N	N
Sense uncertainty	√	√	√	√	√	√
Optimal control	√	P	N	√	√	√
Recovery control	√	N	√	N	N	N
Feedback mechanism	√	√	√	√	√	√
Self-healing mechanism	√	N	N	N	N	N
Inhibition of failure	√	N	N	N	N	N
Isolate/repair fault	√	N	√	N	N	N
Controller reconfiguration online	√	N	√	√	P	√
Internal/external disturbances and faults	√	√	√	√	√	√
The attributes contained in the control method	√: Contain			N: Do not contain		P: Partial contain

Immune control is a self-adjusting, self-organizing, and self-learning immune feedback controller based on immune feedback and learning mechanisms. The immune control system has a memory function (derived from the immune system's ''secondary immunity'' function), which increases the speed of the system's response to abnormal situations. The main functions of the immune control system include immune defense, immune self-stabilization and immune surveillance. This system implements immunity through recognition, learning, and memory. A comparison between the immune control and self-healing control is presented in Table 4.

5) SUMMARY

Self-healing aims to recover the original performance index when the system fails. Fault-tolerant control is used to maintain the system running under acceptable performance indicators by reducing the performance indicator. Adaptive control is the adaptation of a system to an external time varying or unknown environment.

A detailed analysis and comparison are provided in Table 5. For the convenience of understanding and comparison, ''√'' indicates that one attribute is contained in the control method. For example, the attribute of ''feedback mechanism'' is contained by all control methods, so the corresponding row is represented by ''√''. ''N'' refers to the attribute not included in one control method. ''P'' represents that an attribute is partially contained in one control method. From Table 5, it can be observed that the self-healing control system involves a wider range of attributes than other control methods. For example, the parameter adjustment attribute in self-adaptive control reflects the adaptability of self-healing control, and online adjustment in active fault-tolerant control demonstrates fault tolerance. *That is, a self-healing control system should be fault-tolerant, self-adaptive and self-recovery. In other words, these control methods lay a foundation for the realization of self-healing control. Self-healing control is an automatic control method driven by artificial intelligence, which has the ability to predict and identify abnormal conditions of the system.*

From the comparison and analysis of self-healing control with fault-tolerant control and adaptive control in Tables 1 and 2, it can be concluded that fault-tolerant control and adaptive control are the basis of self-healing control, and self-healing control is an expansion of fault-tolerant control and adaptive control. The most significant feature of self-healing control is its explicit emphasis on the self-recovery function. In contrast, fault-tolerant control and adaptive control did not emphasize this.

In the comparison between Table 1 and Table 2, from the concept, control objects, control characteristics, control objectives, and overall working state of the system, self-healing control involves a wider range of research, including fault-tolerant control research and the uncertainty of adaptive research. At the same time, fault-tolerant control usually takes measures for some specific component failures in the system, whereas the self-recovery of self-healing control is considered from the system level.

Fault-tolerant control emphasizes ''error tolerance'' but does not emphasize recovery. Simple adaptive control does

not involve the ability to deal with faults but only considers the uncertainty of the parameters and models in the system. Self-healing control considers and deals with these two problems simultaneously. The scope of self-healing control is relatively broad. It can also be concluded that the problem solved in self-healing control is more comprehensive.

V. RESEARCH ISSUES AND PROSPECTS OF SELF-HEALING CONTROL SYSTEMS

A. RESEARCH FOCOUS OF SELF-HEALING CONTROL SYSTEMS

Self-healing control systems are complex systems with multiple subsystems that have the abilities of self-monitoring, self-diagnosis, self-decision and self-repairing. Moreover, it integrates self-optimization control, prevention control, and repair control and can realize fault suppression and fault repair. The distinctive features include the prevention, suppression, and elimination of faults and external interference. Meanwhile, self-healing control system is system of systems (SoSs) consisting of large numbers of subsystems. Thus, achieving consistency control in self-healing control systems is a problem that must be investigated. Furthermore, what needs to be emphasized is that self-healing control system is an advanced stage of intelligent control system with self-healing, which needs a powerful monitoring and detecting subsystem. Hence, a self-monitoring system is essential for achieving self-healing control.

Additionally, it is necessary to explore self-healing theory or self-healing control theory from the perspective of biological self-healing. Investigating the control system from the perspective of wholeness rather than fragmentation will be the focus. Moreover, in the process of exploring biological self-healing, research on the dynamic properties of self-healing control systems is challenging. It is important to break down the barriers between multiple disciplines and form self-healing control of multidisciplinary integration.

B. PROSPECTS OF SELF-HEALING CONTROL SYSTEMS

Self-healing control is still at the stage of concept proposal and formation, and there is still much work to be done to become a relatively independent research topic. Combined with the definitions and characteristics presented in Section IV-A, it is believed that self-healing control will be further developed in the following fields.

Large-scale distributed control systems. Most control systems comprise multiple subsystems with hierarchical relationships. Subsystems must not only realize their autonomy but also achieve coordinated control between them. Large-scale distributed control systems (DCSs) are SoSs that have multiple subsystems. Distributed control systems exhibit the characteristics of decentralized control and centralized management, which are consistent with the distributed management of self-healing control systems.

Intelligent control systems. A self-healing control system is the embodiment of system autonomy and intelligence. Reflecting on intelligence and autonomy is significant. A self-healing control system consists of many subsystems, and each subsystem with self-healing ability is intelligent and autonomous. The computation and complexity of a control system can be reduced by assigning control tasks to the multiple self-healing subsystems. The information processing ability of the entire system can be improved by applying self-healing control to intelligent control systems.

Networked Control Systems (NCSs). NCSs are distributed control systems that provide significant convenience to a transmission medium over a network. Owing to the introduction of the network, the system is facing security risks, not only network-induced factors and traditional faults, but also cyber-attacks. Owing to the distributed management of self-healing control, the optimal control and management of NCSs can be achieved. The impact of an attack on a system can be eliminated by self-healing control. In addition, both faults and attacks can be addressed by memorizing, identifying, and classifying self-healing control systems.

C. FUTURE RESEARCH DIRECTIONS OF SELF-HEALING CONTROL SYSTEMS

With the increasing complexity of modern control systems, higher requirements have been proposed for the self-healing and autonomy of systems. When the system fails, it needs to detect, diagnose, and repair the fault by itself without human intervention so that the system has the ability of self-maintenance and self-management.

According to the definition and characteristics of self-healing control, combined with the development trend of autonomous control in complex control systems, some research directions for self-healing control are provided.

1) Self-healing control makes use of system state diagnosis technology and advanced control to provide the system with the functions of state online diagnosis, real-time online optimization, prevention of potential faults, self-healing of known faults, and adaptive repair of unknown faults. Therefore, self-healing control is combined with a system with adaptive ability to study the dynamic threshold problem of the system, deal with small faults, and distinguish faults, noise, and uncertainties in the system. Enable system faults can be distinguished and diagnosed accurately.

2) Because of the self-detection and self-diagnosis ability of self-healing control, the system has a strong identification. Self-healing control combined with machine learning methods, such as deep learning, has great development potential for the system identification of faults and anomalies.

3) Aiming at the security problem of complex control systems, event-driven control, model predictive control, and resilient control are combined to address the security problem of the system under malicious attack.

4) Regarding multi-agent, unmanned aerial vehicle and unmanned vehicle, the consistency and formation problems are researched in combination with graph theory.

5) The self-healing function of self-healing control is considered at the system level and not only the self-recovery of

a certain component in the system. Because a self-healing control system is a complex system composed of many subsystems, self-maintenance and self-management of the system are required. Considering the autonomy of the system, self-healing control will contribute to the autonomous and intelligent development of the system. Self-healing control combined with deep learning, expert systems, and data-driven research directions will lead to a breakthrough in the field of artificial intelligence.

VI. CONCLUSION

The application of self-healing technology is widely used. Bionic self-healing and self-healing systems are analyzed from a biological point of view in this study. Self-healing systems are distributed in complex systems composed of a large numbers of subsystems that have the abilities of self-monitoring, self-diagnosis, self-decision, and self-repairing. Each subsystem realizes health maintenance and management of the overall complex system with mutual communication. Self-healing, self-optimization, self-defence, and self-recovery without human intervention can be realized in the system, which is a manifestation of intelligence and autonomy.

A self-healing control system is established based on the self-healing system combined with a control idea. The definition, theoretical framework, and characteristics of the self-healing control system are proposed. The self-healing control process includes four stages: self-optimization, self-diagnosis, self-decision, and self-repairing. Self-healing control is not considered a new control method, but an expansion of existing control methods, which will create systems with self-healing properties. The development of the self-healing theory is still in its infancy. Considerable efforts are required to apply self-healing theory to control systems in order to establish self-healing control theory. Moreover, owing to the advantages of self-healing control, it will be investigated in some cutting-edge research directions, such as, (1) Combining event-triggered control, model predictive control, and possible problems in conducting these studies. (2) Integrating deep learning, data-driven, and expert systems to investigate related problems. (3) Applying to multi-agent and unmanned (aerial) vehicle when conducting a study.

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HUAQING LIANG received the B.Sc. degree in measurement and control technology and instruments from the North China University of Science and Technology, China, in 2012, and the M.Sc. degree in control engineering from the Hebei University of Science and Technology, China, in 2016. She is currently pursuing the Ph.D. degree in control science and engineering with the School of Electronic and Information Engineering, Beijing Jiaotong University.

Her research interests include networked control systems and self-healing control.

XUNHE YIN received the Ph.D. degree in control science and engineering from the Harbin Institute of Technology, China, in 2000. He was a Postdoctoral Scholar with the Department of Electronic Engineering, Tsinghua University, from 2000 to 2002 and an Associate Research Fellow with the Academy of Opto-Electronics, Chinese Academy of Sciences, from 2002 to 2005. He was a Visiting Scholar with the School of Electrical and Information Engineering, University of Sydney, Australia, from 2011 to 2012, and with the Department of Engineering, Lancaster University, U.K., from 2017 to 2018. He is currently a Professor with the School of Electronic and Information Engineering, Beijing Jiaotong University.

His research interests include networked control systems, self-healing control, and cognitive control.