Bionic Artificial Self-Recovery Enables Autonomous Health of Machine

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Abstract
This paper explores Engineering self-recoveries theory, which emerged from the research of Bionics to meet the great demand of modern high-risk process manufacturing and the development of aerospace vehicles. Bionics opens a new era in which artefacts learn from natural objects. With the rapid development of the industrial Internet and Artificial intelligence technology, we have gained a deep understanding of the law of fault generation and development, which provides an opportunity for the emergence of Engineering self-recoveries theory. Engineering self-recoveries expands the research field of Cybernetics and Engineering cybernetics, endows machines with the self-recovery mechanism, which is unique to humans and animals, and enables machines to store, supplement and activate self-recovery power to maintain body health. Bionics research on Artificial intelligence has greatly enhanced the function of imitating the human brain, but has ignored the important system and function of humans and animals to maintain their own health—the self-recovery system and self-recovery function. Artificial intelligence imitates the conscious thinking control behaviour of the human brain to realize automation and intellectualization, making machines smarter. Artificial self-recovery can imitate the self-recovery mechanism of human unconscious thinking, and prevent and suppress faults in operation to realize self-recovery, possibly making machines healthier. Artificial self-recovery technology includes self-repair, compensation, self-protection and self-recovery regulation. Engineering self-recoveries is the basis of the autonomous health of machines and even artificial systems, and a new research field of Bionics. This has broad application prospects in engineering.

Keywords  Engineering self-recoveries · Bionics · Artificial self-recovery · Artificial intelligence · Fault self-recovery regulation

1  Bionics Opens a New Era in Which Artefacts Learn from Natural Objects

Since ancient times, nature has been the source of all kinds of technical ideas, engineering principles and great inventions of human beings. As an independent discipline, Bionics was officially born in September 1960. The first Bionics conference was held at Dayton Air Force Base in Ohio by the U.S. Air Force Aviation Administration. The central theme of the conference was "whether the concepts derived from the analysis of biological systems, can be applied them to the design of artificial information processing systems". American J.E. Steele named the emerging science "Bionics," which means the "science of the function of living systems" in Greek. Steele defined Bionics as "the science of constructing technical systems by imitating biological principles, or making artificial technical systems have or resemble biological characteristics" [1]. In short, Bionics is the science of imitating biological systems and building technical systems by imitating biological systems.

In the evolutionary course of survival of the fittest over hundreds of millions of years, natural organisms have optimized many excellent structures and special functions for various needs, such as survival, self-defence, competition and development, which have brought unexpected inspiration to the innovation of human science and technology. Since ancient times, nature has always been a source of inspiration for human unconscious and conscious bionic behaviours. In the process of the evolution of civilization,
human beings have been constantly inspired by nature. Now, a new era of learning from nature has been opened [2].

The great ancient Chinese thinker Laozi incisively discussed the law of the occurrence and development of things. He said, "Everything under heaven comes from something, and something comes from nothing." Nature’s greatest creations are living things (including man); in this world, trillions of floating atoms have somehow come together to create man in complex and strange ways. Man’s greatest creations are tools and machines. Machines imitate natural objects to create artificial objects. Modern machines are an important symbol of human progress and civilization. Modern society is defined as the coexistence of biology, society and machines (artificial creation). Wm A Wulf, President of the American Academy of Engineering, called it BASOMA (Biology-Society-Machine) [3].

With the development of modern information technology and Cyber Physical System (CPS), Cyber (meaning control, communication, collaboration, virtual, these meanings include computation) should also be added to the basis of the Biology-Society-Machine. Collectively known as the BASOMACY (Biology-Society-Machine-Cyber), as shown in Fig. 1. The emergence of Cyber as a system is quietly changing the world.

In a sense, machines are a continuation of biology by other means, as we look at the evolution of our planet from single cell to vast societies. From a Bionic point of view, the struggle against machine malfunction can be viewed as a continuation of the struggle against disease in another way. From the perspective of the history of human disease and treatment, as shown in Fig. 2, human disease has a history of 3 million years, while real medical activity to address disease has existed just ten thousand years. This demonstrates that throughout human history "no cure without medicine" has been the mantra for more than 99% of history. Regardless, people have not been decimated by diseases. It is relied on the self-organization mechanism of life, is the mechanism and ability of the body to defend, adjust and adapt to the complex effects of the internal and external environment, and it is the mechanism and ability of the body to autonomously regulate, return to normal and maintain stability in response to its own abnormalities (lesions) [4]. It is easy to see that the history of people's struggle with diseases encompasses a long period of complete reliance on "self-recovery", from which the concept of "cure" gradually emerged, forming the coexistence of the two ways so far.

From 1781, when Watt improved the steam engine, to 1800, when it was widely used in industrial production, the
history is only more than 200 years. People struggle with the fault is mainly to rely on "cure", that is, the machine out of fault to shut down by the people to repair. Everything in the universe follows certain objective laws. Whether people can follow the common law in their struggle against malfunction and disease, and whether they can emulate the unique self-recovery function of humans and animals to create and develop the self-recovery function and apply it to machine failure is an important subject worthy of Bionics theoretical exploration.

The theory of dissipative structure reveals the inner relationship between living system and non-living system, and points out that there is no strict boundary between the two kinds of systems; people follow some common laws when they struggle against malfunctions and diseases. Based on "self-regulation is the first principle of therapeutics" in traditional Chinese medicine, a new concept of "Engineering self-recoveries theory" is proposed and studied in this paper. The theory of Engineering self-recoveries refers to the scientific theory that the machine can restrain and eliminate the fault by itself during the operation, and it is the development inevitable trend of the intelligent diagnosis and treatment of machine faults.

2 Cybernetics and Artificial Intelligence are Derived from Bionic Research

The emergence of Cybernetics and Artificial intelligence is the result of Bionic research. During World War II, Norbert Wiener was involved in research on the automatic control of artillery. He drew an analogy between the action of a gun shooting an aircraft and the action of a man hunting and discovered the important concept of feedback. He believed that purposeful behaviour can be replaced by feedback, thus breaking the boundary between living and non-living, and endowing the concept of purposeful behaviour, which is unique to human and animal, to machines [4].

The emergence and development of Cybernetics build a bridge for the connection between biological system and technical system. This new discipline not only breaks through the boundary between animal and machine, but also breaks through the boundary between control engineering and communication engineering. He gave machines the purposive behaviour of animals and makes an analogy between some mechanisms of animals and machines, thus grasping the common characteristics of all communication and control systems and synthesizing them at a more general height, thus forming a new theory with more general significance [4].

Mr. Qian Xuesen was engaged in the mechanical research in the development of the supersonic aircraft, rockets and jet propulsion aircrafts in the United States. He had a complete understanding of how important the interrelationship between engineering practice and scientific theory is. In the rocket research, he found that no matter the maximum range, course control, combustion stability or other problems need to have new theories and new technology to solve. The pure mechanical theory cannot completely solve the practical problems of this kind of engineering technology. It is precisely under the ideological guidance of the combination of scientific theory and engineering practice that he applied Cybernetics to engineering control and automatic regulation technology and founded a new discipline—Engineering cybernetics, which changed the situation that Cybernetics, engineering control and automatic regulation practice were separated [5]. This paper fully embodies and expands the thoughts of Wiener's Cybernetics. It is another classic monograph that creatively discusses control and guidance.

Artificial intelligence was formally proposed by McCarthy at the Dartmouth Academic Conference in 1956. Artificial intelligence was also derived from the idea of Bionics, although the concept of Bionics had not yet been formally proposed. In its essence, Artificial intelligence is a simulation of the thinking processes of the human brain, aiming to make computers think like humans and have the same thinking functions as the human brain. Artificial intelligence is a new technical science that studies and develops theories, methods, technologies and application systems used to simulate, extend and expand human intelligence [6]. At present, it is known as one of the three most advanced technologies in the world.

Broadly speaking, Artificial intelligence is about the intelligent behaviour of artificial creation, and a long-term goal of Artificial intelligence is to invent machines that can perform the above behaviours as well as or better than human beings. Another goal is to understand whether such intelligent behaviour exists in machines, humans or other animals. Therefore, Artificial intelligence contains the dual goals of science and engineering [7].

3 The Rise of High-risk Process Equipment and Aerospace Vehicle has Led to the Emergence of Engineering Self-recoveries

3.1 Bionic Theory Led to the Birth of Engineering Self-recoveries to Meet Major Engineering Demand

Machine is a double-edged sword, which can bring blessing to human beings, sometimes may bring disaster to human beings. A fault in a machine can lead to damage to its components, causing possible interruption of production and major accidents. In petrochemical, coal chemical,
metallurgy, electric power, nonferrous metal and other modern high-risk complex process industries, mechanical equipment is becoming increasingly large, high-speed, automated and intelligent. This is especially true in high-speed turbine machinery, compressors, pumps, fans and other major equipment closely linked with the production process, forming a large system. An unplanned shutdown leads to significant losses, and failure may also lead to machine destruction, death, explosion, pollution and other catastrophic events. Aerospace vehicles cannot be repaired by humans while in operation, which may lead to the inability to complete the flight mission and even the occurrence of aviation and space accidents.

With large-scale production and continuous improvement of the degree of automation, the status of fault prevention and maintenance in modern enterprises has become increasingly important. According to statistics, in some modern enterprises, equipment breakdown maintenance and downtime loss costs are getting higher and higher, accounting for approximately 30–40% of its production costs, in some industries, maintenance costs have risen to second place in the total cost of production, or more. The maintenance cost of the aero engine is much higher than design and manufacturing costs. Fault and accident prevention and control is an increasingly important subject faced by modern enterprise management.

So far, to prevent accidents, the international engineering science and technology community has taken two countermeasures to combat the operation failure of machines and production devices:

1) In the modern process industry, critical equipment is equipped with an Emergent Shut Down (ESD) system to prevent failures from causing machine damage and other accidents. With the widespread application of distributed control system (DCS), an increasingly abnormal operating alarm system is set up, which plays an important role in protecting production equipment, but some failure shutdown would cause great economic losses.

2) Remote condition monitoring and diagnosis technology based on the industrial Internet and implement condition-based maintenance, predictive maintenance and remote intelligent maintenance has been developed and applied.

In recent decades, the complexity and automation level of production equipment has increased significantly, making engineering increasingly risky and leading to the impossibility of complete reliance on human troubleshooting in some occasions. Remote intelligent maintenance of equipment is also far from able to meet the major needs of intrinsically safe and unmanned operations in high-risk industries. There is an urgent need to develop new theories and methods to combat equipment failure and change the traditional way of relying only on emergency shutdown mechanisms to protect the machine and completely by people to "cure" the failure. This theory and methodology are different from equipment diagnosis and predictive maintenance technology. They aim to enable the equipment system to engage in self-recovery, initiating regulation in operation and eliminating faults or repair defects autonomously, instead of shutting down and requiring troubleshooting by people.

Living organisms have functions far superior to those of any artificial bionic machine yet built. Bionics is a science that studies how to build technical systems by imitating biological systems. Bionics studies the structure, function and working principles of organisms and transplants these principles into engineering technologies to invent instruments, devices and machines with superior performance and create new technologies. Bionic mechanics is an important branch of Bionics. Its main work is to study the mechanical devices or electromechanical devices to imitate the structure and motion characteristics of organisms, so as to design electromechanical devices similar to the organisms [8].

From the understanding of general electromechanical systems in the academia of the United States, Germany, Japan and other developed countries, the essential feature of advanced complex electromechanical systems is mechatronics, which is a modern mechanical system that makes full use of the information processing and control functions of computers and the characteristics of controllable driving components and realizes the intelligence and automation of the mechanical system. The widely accepted view of Bionic mechanics in the international academic community is the "Five function theory" proposed by Rolf Isermann of the University of Darmstadt in Germany, that is, the composition and function of the modern electromechanical system and the corresponding human organs can be divided into the following five parts [9], as shown in Fig. 3.

The control function of the electromechanical system is popularly likened to the human brain;

The dynamic function is similar to the human visceral digestive system;

The sensing and detection function are likened to the human five senses;

The operating function are likened to the human limbs;

The structural function is likened to the human body;

This view has been recognized by many international scholars. It can be seen that the self-recovery system and self-recovery function have not been included in the bionic components of electromechanical systems in international academic circles. From the perspective of bionic design, the construction of a modern electromechanical system is based on the "five function theory", which is incomplete. Therefore, bionic design should be considered to endow
the machine with the self-recovery function of humans and animals.

The current bionic mechanical theory studies how to imitate the activity ability of humans and animals, namely, the "purposive behaviour" said by Cybernetics, so that the machine has the operation function but neglects the other important system and function of humans and animals to maintain their own health—the self-recovery system and self-recovery function. In fact, Artificial self-recovery and Artificial intelligence is both Bionics research fields, as shown in Fig. 3.

As the scale of artificial systems increases, their safety and autonomous health cannot be achieved by Artificial intelligence and intelligent control alone. What principle and method to apply, how to realize the machine to suppress abnormal condition, prevent the occurrence of failure during operation, that is, how to make the machines has the function of self-recovery, this is the problem that Bionics has not been involved in so far.

Biomedical science has developed to such a stage that the study of self-regulation functions such as immunology has become the biggest challenge to medical science. The study of self-regulation pattern recognition, the study and simulation of the unconscious thinking process of the immune system, the reliability and coordination of autonomous regulation in organisms are important aspects of Bionics medicine research. Biology, including humans, is a model of Bionics. The research results of self-regulation function, such as biomedical immunology, can be guided and applied to the research of Engineering self-recovery theory and Artificial self-recovery as well as the research of Artificial intelligence.

Modern machines tend to be more and more automatic and intelligent, their structure is more and more complex, and its function is more and more perfect. Like the living organism, a machine is actually a complex system composed of many interrelated and interacting elements. It is also in a certain organization (order) and diversity (complexity) in a certain stable state, and through the interconnection and interaction between the various systems, process regulation is achieved and system optimization is maintained in a stable state. Artificial self-recovery has broadened the research field of Bionics. Similar to bionic creation of intelligent control systems, Bionics should study the concept of a self-recovery mechanism, unique to humans and animals, to create a new self-recovery system for machines. The machine self-recovery system should be a cooperative, dynamic system that can store, supplement and mobilize the self-recovery power of the machine to maintain the body's health. This should become the new field and important direction of Bionics research.

3.2 Domestic and International Development History of the Fault Self-recovery Principle

According to the literature [10], the earliest reference to self-healing control can be traced back to the concept of self-healing control proposed by scholar Briley in the field of computer in 1968 [11]. In 1984, the United States promulgated and implemented the "Outline for Self-healing of Flight Control Systems" and began to study models with self-healing ability. In 1997, the "Outlook 2010 Next Generation Manufacturing Plan" proposed by the United States listed self-maintenance and self-repair as one of
the researches focuses [12]. In 1999, the Electric Power Research Institute of the United States and the Department of Defence first proposed the concept of a self-healing power grid in the "complex interactive network and system program" and embraced self-healing control as an important research field, thus, self-healing control in the field of power grids was formally proposed.

The theory of Engineering self-recoveries originates from the great demand of large modern industries, especially the highly automated high-risk processes manufacturing industries. In 32 years of engineering practice in petrochemical enterprises, the author realized that, except for a few faults, most faults have a gradual process, and interaction is the ultimate reason for failure. If caught early and appropriate measures are promptly taken, the role of restraining or countering faults in the operation can prevent failure. Due to the lack of advance consciousness of "nip in the bud" in concept, the gradual process of fault occurrence has not been paid attention to from the design and manufacture of equipment to its operation, and the good opportunity to regulate or suppress the fault has been missed, leading to the occurrence of equipment failure and even accidents.

With the rapid development of computer over the past decade, Artificial intelligence and control technology, especially industrial Internet and data science and engineering, the real-time monitoring and diagnosis technology of equipment has become increasingly mature. The new scientific concept of twenty-first century medicine proposed by the WTO, with human health as the main goal, has led to an increasingly profound understanding of the law of occurrence and development of equipment faults. Fast and accurate fault source tracing diagnosis makes real-time precise and stable suppression of faults possible. This has laid a theoretical foundation for bionic Artificial self-recovery and autonomous health of equipment and even artificial system.

In November 2003, the author proposed the principle of machine fault self-recovery for the first time in the "International Academic Conference on Intelligent Maintenance" [13], which attracted the attention of academic circles. Under the guidance of System theory, transplanting the idea of the "self-recovering" therapeutic method in medicinal science, with the prevention and self-recovery of faults as the goal, this paper formally puts forth the fault self-recovery principle of process equipment.

In 2006, the author and his team undertook the key project of the National Natural Science Foundation of China "Modelling and simulation, operation optimization and self-recovery theory and methods of mechanical complex systems".

In 2006, the Chinese Academy of Engineering consulting project "Suggestions on the popularization and application of equipment fault self-recovery engineering in China" pointed out that equipment fault self-recovery engineering can effectively prevent and eliminate faults and accidents, which greatly improves the safety reliability of process industry production and can achieve 7 positive outcomes: (1) reducing failures and accidents, (2) reducing downtime production losses, (3) reducing "excess inspection and testing", (4) reducing "excess maintenance and repair", (5) reducing pollution, and (6) reducing equipment dependence on people [14].

NASA statistics show that of the 126 uncontrolled flight incidents, 94 percent were caused by adverse onboard conditions, and of these, 45 percent were caused by system failures, damage and errors [10].

In 2007, NASA started a research program called "Integrated Resilient Aircraft Control" to enhance the self-healing and capability of the flight control system [15].

In 2009, Rieger from Idaho National Laboratory puts for ward the concept of self-healing control of industrial control systems for the first time. He pointed out that a self-healing control system essentially means that the system has a function to ensure that the industrial control system can still recover the ideal system under the condition of any harmful behaviour that may reduce the system performance [10].

In 2010, the author formally proposed the theory of Engineering self-recoveries at the 23rd International Conference on Condition Monitoring and Diagnostic Engineering Management (COMADEM 2010) in Nara, Japan.

In 2011, the author and his team undertook the key project of the National Natural Science Foundation of China "Dynamic behaviour of complex electromechanical system of turbine machinery and principles and methods of target ing vibration and noise suppression".

In 2012, the National Science Foundation of the United States launched a research program named the "Fail-Resistant System", aiming to further popularize the concept of a self-healing control system [10].

The literature [16, 17] in 2015 incorporated fault diagnosis and fault-tolerant control into the unified framework of self-healing control. The self-healing control system is still in the concept and formation stage and remains under development. According to the existing data and literature, the landmark development year of self-healing control is summarized as 2015. The timeline of the development of self-healing control is shown in Fig. 4 [10].

It is not difficult to see that the self-healing systems proposed by American scholars are all in the fields of computers, power grids, aircraft and industrial control systems, mainly to ensure the performance and function of the system. The self-healing control of mechanical equipment systems has not been clearly put forth, nor has the concept of autonomous health of equipment been put forward.

Artificial self-recovery refers to a self-recovery mechanism that enables mechanical equipment to achieve autonomous self-healing faults and autonomous preventive
supress faults during operation. As shown in Fig. 5, Artificial self-recovery can be divided into autonomous self-healing faults and autonomous preventive faults. The autonomous self-healing faults include the following:

1) Self-repair, that is, self-repair damaged parts in operation;
2) Compensation, switching thermal backup to replace damaged or lost functions of hardware and software systems;
3) Self-recovery regulation, fast accurate fault tracing diagnosis, finding out and counteracting the fault causes, to eliminate the fault in operation;

The autonomous preventive faults include the following:

1) Fault prevention: in the case of interference or human misoperation, real-time response measures should be taken to prevent the fault from occurring;
2) Self-protection: online technical measures should be taken to prevent damage to machine and parts;
3) Self-recovery regulation: during operation, the conditions of fault generation are predicted and suppressed in real time so that the fault does not occur.

4 Artificial Intelligence and Artificial Self-recovery Mimics the Different Thought Methods of the Human Brain and Body

Artificial intelligence and Artificial self-recovery are both new functions endowed by humans to machines. Artificial intelligence mimics the human brain, and Artificial self-recovery mimics the human body, is different ways of thinking. While Artificial intelligence imitates conscious thinking in the human brain, Artificial self-recovery imitates unconscious thinking in the human body, which does not naturally evolve as humans do. Of course, for a machine, whether it imitates the conscious thinking of the human brain or the unconscious thinking of the human body, there is a bionic simulation of its function. As some experts have pointed out,
machines are material, and the material that makes them up does not have the property of thinking. Some of the functions of a computer are as good as or even better than that of a human brain, but that is only a functional simulation, not that the material that makes up a computer has the mental properties of a human brain. Human thinking is the unique property of the brain, a special substance that was formed only in the 20 billion years of the evolution of the universe [18].

It has been only 200 years since human beings created machines, and there is still a long way to go to gradually evolve and for perfect machines. Therefore, whether Artificial intelligence simulates conscious thinking to make machines smarter or bionic Artificial self-recovery simulates human unconscious thinking to make machines autonomously healthy, they all imitate the human brain and human body from the perspective of Bionics to study a new generation of machines with intelligent and self-recovery functions. This is undoubtedly transformative and significant progress in human science and technology.

### 4.1 Artificial Intelligence Mimics the Human Brain Conscious Thinking Makes Machines Smarter

As the name implies, the Artificial intelligence means to use artificial methods to achieve intelligence on machines (computers), to simulate human intelligence on computers, or to make computers as intelligent as people. Now, the terms "Artificial intelligence" has been used as the name of the science "how to realize human intelligence on machines". In this sense, it can be defined as follows: Artificial intelligence is a subject that studies how to construct an intelligent machine (intelligent computer) or intelligent system, so that it can simulate, extend and expand human intelligence. Generally speaking, Artificial intelligence studies how to create machines that have the ability to listen, speak, see, write, think, learn, adapt to changes in the environment, and solve various practical problems. In a word, it is to make the machine can do the work that requires human intelligence, even faster and better than humans [19].

Although, it is still difficult for modern science to fully reveal the specific mechanism of thinking generated in the human brain, it is reasonable to affirm that the human brain is the only organ of thinking activity. Of course, the human brain cannot do without the coordination and cooperation of other organs in its thinking activities. Regardless, their role, however important, is indirect, and it can only be regulated by the human brain through neural connections to play a specific role. For thinking, the direct effect can only be found in the brain [20]. The human brain is the only organ for thinking activities, as shown in Fig. 6 [21].

As a science, the goal of Artificial intelligence is to make machines have the intelligence to do things like humans [22]. The answer to the question "can machines think?" is therefore crucial to the discipline of Artificial intelligence [23]. The generation of a modern electronic computer is a simulation of the thinking function of the human brain and the information process of human brain thinking. A comparison of information processing between the human brain and computers is shown in Fig. 7 [24].

In essence, Artificial intelligence is the simulation of the information process of human brain thinking, namely conscious thinking. Artificial intelligence aims to make computers think like humans and make machines have the thinking function of human brains. Intelligent equipment is a machine that can autonomously or interactively perform various anthropomorphic tasks in various environments. Artificial intelligence will make the machine smarter.

### 4.2 Bionic Artificial Self-Recovery Mimics Human Unconscious Thinking and Makes Machines Autonomously Healthy

Bionics research on Artificial intelligence has greatly enhanced the function of imitating the human brain, but ignored the important system and function of humans and animals to maintain their own health—the self-recovery system and self-recovery function. The self-recovery system is a collaborative dynamic system in which organisms store, supplement and mobilize self-recovery power to maintain body health. The high-level biological self-recovery system, found in humans and animals, includes several subsystems, such as the immune system, excitation system, self-repair system and endocrine system.

It is generally believed that consciousness is the indirect and generalized subjective reflection of the human brain to objectify things; that is, consciousness is the response of the human brain to stimuli. The body's self-recovery mechanism
does not go through the brain; thus, it belongs to unconscious thinking. Unconscious thinking inherits and deepens the bioelectric autonomous operation mode of the nervous system in the original thinking, while conscious thinking strengthens the sensory system of the person centred on my attention. Because the sensory system is focused on the perception of the external environment, the perception of the autonomous operation of bioelectricity in various systems in the body is lost. As a result, people do not know how bioelectricity operates, how endocrine substances are involved, and how bioelectricity runs out [21].

Unconscious thinking, that is, the movement of mind that the subject is not aware of, but exists objectively. The unconscious thinking of an organism guides its own physiology, growth and development, wound repair, disease resistance, reproduction and variation [25]. This process of "unconscious thinking" is carried out by an agent that is almost a second self. The self-recovery mechanism of the human body belongs to unconscious thinking, as shown in Fig. 8 [21].

From the perspective of System science, the immune system is a distributed and complex adaptive giant system composed of special chemical molecules, cells, tissues and organs [26]. According to the traditional viewpoint of immunology, its main function is to recognize the external substances entering the organism and judge whether they are harmful to the body [27]. If the substance is harmful, the system responds to it by removing the harmful intruder.

As shown in Fig. 9, the subject of the immune system uses pattern recognition, learning and memory to detect, perceive and identify the internal information of the external invading object and generates cognition of the invading object through a variety of ingenious information fusion and processing means. Distinguishing oneself from non-onself will eventually produce an immune response based on cognitive results [27]. The immune system is as complex as the brain, it is known as the second brain. The difference is that the brain centrally controls the body's purposeful behaviour functions, while the immune system and all self-recovery functions are distributed throughout the body.

The principle of self-repair is a biological concept. Organisms have the ability to self-adjust their structures to prevent damage and recover by sensing external environmental information, that is, they have the function of self-repair. For example, after the skin is damaged, the human body can automatically repair the skin to make the wound heal through a self-repair function. Many organisms in nature have the ability to repair themselves. For example, the life span of some trees can reach ten thousand years, while traditional artificial materials cannot reach such a long life span due to their lack of self-repair ability. The human immune system and self-recovery system are self-recovery mechanisms and systems to ensure human health and safety under complex environment. The modern machine system is the deep integration of machinery and information systems, so from the perspective of Bionics, this mechanism
Fig. 8 The human body’s self-recovery mechanism belongs to unconscious thinking [21]

Nervous system—sensors and transmission of information (through the cable network) and diagnosis, prediction and self-recovery decision-making system.

Information system—the dynamic characteristics of the machine itself and the energy, material, information input and output and its signal processing system.

Exciting response system—rapid recognition system for abnormalities.

Immune system—a system that counteracts the causes and conditions of failure occurrence.

Repair systems—self-repair system.

For a machine, of course, mimicking the unconscious thinking of a human body mimics its self-recovery mechanism. The machine is material, and the material that constitutes the machine is completely different from the human body. It is not the material that makes up the self-recovery system that has the property of human unconscious thinking. The self-recovery system can recover some faults in ways that human beings cannot, but it is only a simulation of the self-recovery mechanism, with the nature of the unconscious thinking of the human body.

and system also has reference significance to the health of mechanical systems.

Engineering self-recoveries theory and fault self-recovery regulation systems are new research directions of Bionic mechanics. Based on the failure mechanism and risk analysis, the machine self-recovery system is a cooperative dynamic system that can store, supplement and mobilize the self-recovery power of the machine to maintain its health state. The machine self-recovery system makes the machine have not only the adaptability of parameter adjustment, but also the adaptability of structure. The self-recovery power of the machine includes compensatory power, cleaning power, repair power, self-adaptive adjustment power, exciting power, immunity, self-protection power, synergistic power and so on. It will inhibit the damage power that the machine may produce so that it does not produce or eliminate the fault in the operation. Analogous to a human self-recovery system, the bionic self-recovery system of the machine includes the following:

Fig. 9 Information processing mode of the immune system [27]
The human meridian is a neuroendocrine-immune network with sensitive nodes and functional connections. The complex network of the human meridian is not only a system all over the body but also plays a regulatory role in the body through sensitive nodes and functional connections. The nervous system includes the central nervous system and peripheral nervous system [28]. Sensors, information networks, and intelligent controller systems in modern machines are very much like those in the human body.

The Strategic Research Group in Advanced Manufacturing Field of Chinese Academy of Sciences points out [29] that by 2050, the intelligent level of equipment will be substantially improved. According to the change in environment and task, the equipment not only has the adaptability of parameter adjustment but also has the adaptability of structure. Combined with the progress of materials and information technology, it will promote the intelligence level of equipment to realize the advanced intelligent stage of self-maintenance, self-adaptation and self-evolution from the current controllable and automatic level.

According to the change in environment and task, the self-recovery system can make the equipment not only have the adaptive ability of parameter adjustment but also the adaptive ability of structure and promotion of the intelligent level of equipment from controllable and automatic to the advanced intelligent stage of truly realizing self-maintenance, self-adaptation and greatly reducing the dependence on human. Artificial self-recovery is an important way to realize the autonomous health of manufacturing equipment and has broad application prospects.

Artificial self-recovery technology under the guidance of Engineering self-recoveries theory belongs to the research field of Bionics, similar to Artificial intelligence technology. Artificial self-recovery imitates human unconscious thinking and endows machines with the self-recovery mechanism unique to humans and animals. From fast and exact fault source tracing diagnosis based on Artificial intelligence to accurate and stable self-recovery control based on Artificial self-recovery, the traditional way of only relying on fault shutdown to protect the safety of the machine and completely relying on human to repair the machine will be changed to realize self-recovery, which will greatly improve the autonomous health level of equipment.

As mentioned earlier, the research fields of Artificial self-recovery include self-repair technology, compensation technology (including intelligent switching), fault self-recovery control technology, and self-protection (including fault prevention technology), etc. [30].

5 Connotation and Research Fields of Engineering Self-recoveries and Fault Self-recovery Regulation Technology

Mr. Qian Xuesen proposed the following: "Engineering cybernetics is the study of Cybernetics as a science that can be directly applied to the engineering design of controlled or manipulated systems. " "The content of Engineering cybernetics is completely summed up from the actual automatic control technology, no design and use of control system experience, there will never be Engineering cybernetics". Similar to Engineering cybernetics, Engineering self-recoveries are also summarized from actual diagnosis, prediction and active control technology, which is the sublimation of experience and theory of fault prevention and control engineering.

The study field of Engineering self-recoveries is different from those of Cybernetics and Engineering cybernetics. The complex system of mechanical equipment is in an orderly and stable state under normal operation, and the information can represent its structural system, its input and output changes and their interrelated action. When the internal subsystems of the mechanical equipment system itself or its relationship and interaction with the input and output substances, energy and environment are abnormal, it starts to deviate from the ordered stable state and produces faults. The fault symptoms can be represented in real time through the information of monitoring and processing. Therefore, the fault causes and conditions can be self-diagnosed and predicted, and then through the real-time knowledge-based comparison, recognition and self-recovery decision-making, intermediate transformation and self-recovery control actuator, the occurrence and development of the fault can be avoided or restrained.

Engineering self-recoveries theory is a new theory that is formed based on fault self-recovery regulation as the research object. On one hand, fault self-recovery regulation is the research object, research starting point and the basis of theory generalization of Engineering self-recoveries theory. On the other hand, only through further theoretical research, theoretical generalization and theoretical sublimation can obtain a new theory. Engineering self-recoveries theory should not only study the principle and characteristics of fault self-recovery regulation but also study the formation process, technical function and development law of Engineering self-recoveries theory.

Modelling is a mathematical description of people’s understanding of the mutual relations and interactions of objectively existing structural systems. Information can characterize the changes in structural systems and their inputs, outputs, and their interactions. When an abnormality occurs between the internal subsystems of the mechanical...
equipment system or/and its interaction with the environment and input and output, it starts to deviate from the orderly and stable state and causes a fault, the fault symptoms can be monitored and characterized in real time, and self-diagnosis, prediction and regulation can be performed accordingly. The typical mode of the regulation system aiming at fault suppression and elimination of faults, namely, fault self-recovery regulation (FSR), is shown in Fig. 10 [83].

Fault self-recovery Regulation (FSR):
Through real-time monitoring, abnormal operation conditions of the machine are captured, and the fault location and causes and generation conditions are determined using fault source tracing diagnosis and prediction. Then, the causes and fault generation conditions are counteracted during operation by parameter/structure adaptation self-recovery decision and actuator to restore the machine to normal condition.

The self-recovery regulation system can control the machine's own structure and/or the input and output of energy and material through information transmitted by the cable, which can realize fast source tracing diagnosis and accurate and stable self-recovery regulation. The self-recovery regulation system of a machine is a typical Cyber-physical system (CPS). The complex system of mechanical equipment, the input and output of material and energy, as well as the actuator are all physical entities; sensing signals, communication systems, computers, source tracing diagnostics and self-recovery decision-making software all fall under the category of cyber. The self-recovery regulation system is the deep fusion of the two, and the fault self-recovery regulation system should have three parts: (1) self-diagnosis and prediction, (2) comparison-recognition and self-recovery regulation decision making, (3) intermediate transition and actuator. A self-recovery regulation system for fast and accurate source tracing diagnosis and precise and stable self-recovery regulation can be completed. It can do things that human beings cannot do at all, but this function of the machine is entirely endowed by human beings.

The core idea of self-recovery regulation is different from the core idea of intelligent control. Intelligent control is the "direct target", that is, the function of the machine. The application of negative feedback control input is the main form of automatic control, it only monitors the output of the system and does not involve the health condition of the machine itself, so it neither monitors the machine health condition nor controls the condition of the machine. Self-recovery regulation is an "indirect target", which is the cause of fault and the conditions under which the failure occurs, through parameter and structure adaptation to apply the "counteracting effect" in a timely and appropriate amount, so that it does not have the condition under which the failure occurs or counteracts the causes of failure.

In the field of self-recovery regulation and application of rotating machinery, the Diagnosis and Self-recovery Engineering Research Center of Beijing University of Chemical Technology has made the following main achievements in theoretical and experimental research of self-recovery regulation for eighteen years [30, 31]:
- Turbine compressor rotor axial displacement fault self-recovery regulation system [32–34].
- Rotor multi-frequency vibration suppression technology based on fast optimization of electromagnetic force parameters [35, 36].

Fig. 10  Block diagram of the basic principle of the self-recovery regulation system
Targeted suppression of rotor vibration of centrifugal compressor based on electromagnetic damping force [37–39].

Vibration induced by unbalance of multi-rotor shafting and a multi-target self-recovery regulation method based on self-recovery force [40].

Self-recovery regulation of hydrostatic and hydrodynamic film end face seal [41, 42].

Automatic balancing principle and system of rotating machinery [43–46].

Pneumatic liquid unbalance vibration fault targeting self-recovery regulation system [47–49].

Research on electromagnetic driven double balance head and optimal control method of automatic balance [50–52].

Aeroengine vibration fault monitoring and the principle and method of the whole machine dynamic balance [53, 54].

A Review on Self-recovery Regulation Technique Engineering [55].

Principle and method of self-recovery regulation of unbalanced vibration of rotating machinery [56].

Optimal design of novel electromagnetic active balancing actuator with radial excitation [57].

Numerical analysis of tuned mass damping technology for high-rise flash tower [58].

Some technologies have achieved obvious results in engineering applications, for example, using tuned mass damping technology to eliminate the integral gear driven centrifugal compressor, which was introduced from abroad, and pipe strong vibration. Major breakthroughs have been made in the research and experimental verification of aero-engine propeller automatic balance and centrifugal compressor shaft displacement self-recovery regulation.

In recent years, many domestic colleges and universities have carried out research on artificial self-recovery technology with remarkable results. The application of tuned mass damping technology, which was developed by Zhejiang University [59–62] has greatly reduced the high tower equipment wall thickness, reduced the equipment quality from the original design of more than 500 tons to approximately 300 tons, and can ensure the safe and reliable operation of the equipment. An engineering university has made a major breakthrough in the research of "Alignment controllability of air spring vibration isolation system of ship propulsion plant" [63], and the multi-objective self-recovery regulation system has achieved practical results in engineering application. Tsinghua University adopts self-regulation technology in the sealing system, which significantly improves the reliability of the seal device [64].

6 Engineering Self-recoveries and Cybernetics and Engineering Cybernetics

Engineering self-recoveries, such as Engineering cybernetics, is summarized from engineering practice. Engineering cybernetics is a theory about the analysis, design and operation of control engineering systems, which can guide the design and manufacture of machines to realize automation. The theory of Engineering self-recoveries is about the theory of fault self-diagnosis and self-recovery regulation in the operation of machine system, which can guide the design and manufacture of machine to realize self-recovery. The theory of Engineering self-recoveries is a bionic design that provides a theoretical basis and method for developing a new generation machine with a self-recovery function, which is intrinsically reliable, free of maintenance and less maintenance. The self-recovery system can reduce the dependence of the machine on humans, restrain the destructive power of the machine, and make the machine work in good condition to extend the safe and smooth-running period of the machine.

In long-term engineering practice, experts and scholars engaged in engineering control are also aware of the importance of function loss and decline of engineering systems, so they are also studying the theory of fault tolerance to improve the reliability of system functions. The fault-tolerant theory of Engineering cybernetics aims to maintain and restore the function of the system, for which self-diagnosis is also carried out. The system can automatically change parameters and obtain new functions to automatically correct errors, so that the function of the system is not loss and decline; the system can also automatically switch the backup device, thus, restoring the normal function of the system. From the perspective of reliability improvement, Engineering cybernetics and Engineering self-recoveries theory have some similarities, but their research objects and objectives are completely different. The former aims at restoring the engineering system function, while the latter aims at maintaining the autonomous health of the engineering system.

Engineering cybernetics deals with the reliability of systems' functions, which refer to "purposeful behaviour" rather than the health of machines themselves. Engineering self-recoveries theory only studies the health state of the machine itself, that is, it is committed to the research of machine fault fast and accurate source tracing diagnosis, real-time precision and stable suppression of fault that has expanded the research field of Engineering cybernetics.

Both Cybernetics and Engineering cybernetics endue the concept of purposeful behaviour peculiar to man and animals to machines, while Engineering self-recoveries...
| Theoretical category                  | Cybernetics                                                                 | Engineering cybernetics                                                                 | Engineering self-recoveries                                                                 |
|--------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| Generate background and engineering  | During the Second World War, imitation hunting developed a new theory from   | Around the Second World War, supersonic aircraft, rockets and jet propulsion aircraft   | Modern process industrial production is becoming more and more large, complex, automatic,  |
| requirements                        | the study of purposeful behaviour and feedback in the practice of artillery   | development, automatic control technology in military equipment and industrial equipment  | continuous production, huge investment in equipment, unplanned shutdown production loss is  |
|                                     | automatic shooting aircraft                                                 | began to apply, need to have new theories and technologies to solve                     | huge, the aerospace vehicle in operation simply cannot be repaired by people, need new    |
|                                     |                                                                             |                                                                                         | theoretical guidance                                                                      |
| Discipline orientation              | The science that studies the general laws of control and communication in    | A branch of Cybernetics that deals with the analysis, design, and operation of          | An extension of the field of Cybernetics, that deals with the theory of self-diagnosis and  |
|                                     | machines and living societies. It is the science that studies how dynamic    | controlled engineering systems                                                           | self-recovery regulation of machine systems in operation                                   |
|                                     | systems maintain equilibrium or stable states under varying environmental    |                                                                                         |                                                                                           |
|                                     | conditions                                                                  |                                                                                         |                                                                                           |
| Field of science                    | The science of control and communication in animals and machines             | Research in Cybernetics can be directly applied to the engineering of controlled or     | The science of implanting machines with self-recovery mechanisms using bionic principles  |
|                                     |                                                                             | manipulated systems                                                                      |                                                                                           |
| Break through the boundary          | Breaking the boundaries between animal and machine, control engineering and  | Breaking the boundaries between animal and machine, diagnostic prediction and           |                                                                                           |
|                                     | communication engineering                                                   | self-regulation                                                                           |                                                                                           |
| Simulated way of thinking           | Conscious mind                                                              | Conscious mind                                                                            | Unconscious thinking                                                                      |
| Object of study                     | Animals and machines act purposefully                                       | Animals and machines act purposefully                                                    | Maintain the health of the animal and machine itself                                       |
| The bionic characteristics           | To impart to the machine, a biological concept of purposeful behaviour      | To impart to the machine, a biological concept of purposeful behaviour                   | The concept of self-recovery mechanism, which is unique to animals, is given to machines  |
| Field of technology                 | Automatic control                                                           | Automatic control                                                                        | Self-recovery regulation                                                                    |
| Engineering application             | Machine master control system                                               | Machine master control system                                                             | Machine self-recovery regulation system                                                   |
| Significance                         | The emergence and development of Cybernetics build a bridge for the          | Direct the design and manufacture of machines to achieve automation                      | To guide the design and manufacture of the machine to realize self-recovery, so that the   |
|                                     | connection between biological system and technical system. Direct the design |                                                                                         | equipment autonomous health                                                                  |
extends its research field by applying Bionic principle and endows the concept of self-recovery mechanism peculiar to man and animals to machines. The research fields of Engineering self-recoveries theory and Engineering cybernetics are also different. Engineering cybernetics is the basic theory of production process automation and automatic control systems. Engineering self-recoveries theory is the basic theory of self-recovery regulation and autonomous health of production equipment. The comparison of Engineering self-recoveries with Cybernetics and Engineering cybernetics is shown in Table 1.

7 Conclusion

Currently, Bionic mechanics studies how to imitate the activity ability of humans and animals, namely, the "purposive behaviour" said by Cybernetics, so that the machine has the operation function, but neglects the other important system and function that humans and animals have to maintain their own health—the self-recovery system and self-recovery function. The emergence and development of Engineering self-recoveries theory and Artificial self-recovery technology expand the research field of Bionics.

Engineering self-recoveries apply the Bionics’ principle to meet major needs for the development of the high-risk process industry and aerospace vehicles, and to absorb the commonness of many fault prevention and control and innovative design principles used in engineering practice, and to extract scientific theories. Engineering self-recoveries are an interdisciplinary cluster of subjects. It is a scientific philosophical theory or a systematic view and method to observe the world from a new angle.

Both Cybernetics and Engineering cybernetics endue the concept of purposeful behaviour peculiar to humans and animals to machines, while Engineering self-recoveries extend its research field by applying the Bionics principle and endows the concept of self-recovery mechanism peculiar to humans and animals to machines. Engineering cybernetics is the basic theory of production process automation and automatic control systems. Engineering self-recoveries is the basic theory of self-recovery regulation and autonomous health of production equipment.

In fact, bionic Artificial self-recovery and Artificial intelligence are both Bionics research fields. Artificial intelligence imitates conscious thinking in the human brain. Artificial self-recovery imitates unconscious thinking in the human body. Artificial intelligence makes machines smarter; Artificial self—recovery can make the machine autonomously healthy. Artificial self-recovery technology includes self-repair, compensation, self-protection and self-recovery regulation, which will open up a new way for improving the reliability of mechanical equipment even all man-made systems. Artificial self-recovery, similar to Artificial intelligence, has become an interdisciplinary frontier in science and technology.

China has a complete range of industrial equipment and the largest amount of industrial equipment in the world. Interdisciplinary innovation should be encouraged, and research on the basic theory of Engineering self-recoveries and key technologies of Artificial self-recovery should be strengthened. While learning from developed countries to vigorously support digital transformation and upgrading and build smart plants, we should dare to take the lead and vigorously advocate the construction of autonomous healthy plants.

In the future, autonomous health equipment will increasingly become the most important component of productivity and combat effectiveness, Artificial self-recovery will make future mechanical equipment, manufacturing systems and even all man-made systems more autonomously healthy, sending us to an era of self-recovery with broad prospects for development.

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Data Availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Conflict of Interest The author (Gao Jinji) declares that there is no competing interest.

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