Hybrid Intelligence Problems in Intelligentized Welding Manufacturing Systems

Shanben Chen

Abstract This paper discusses the intelligent scientific methods in the complex system produced by the compound application of AI technology in the intelligentized welding manufacturing technology/systems/workshop/factory (IWMT/S/W/F), which are being researched and developed in the hot spot at present, i.e., the hybrid intelligence problems in the IWMT/S. Based on the technological constitution of the IWMT/S, the paper investigates the hybrid or compound, multiple and mixed effects of different intelligent methods and technologies applied in IWMT/S, which includes the hybrid intelligence problems existing in multi-information sensing, knowledge modeling of arc welding process and intelligent control methodology for welding dynamic process, and the hybrid intelligence problems existing in intelligentized technologies for robotic welding process and systems. A IWMW for piles and legs of the offshore platform with the pentabasic structure function of the IWMT is shown, and the HI features of the intelligent pentabasic technology, systems and methodology of the IWMW for the platform and the hybrid intelligent function of the IWMW are analyzed in this paper.

Keywords Hybrid intelligence problems · Intelligentized welding manufacturing · IWMT/S/W/F · Artificial intelligence (AI) · Robotic welding · Multi-information sensing · Knowledge modeling · Intelligent control · Arc welding process

1 Introduction

It is well known that welding technology has experienced the development course of semi-mechanization, automatic welding and robot welding from the traditional handicraft operation [1–5]. It has become an inevitable trend to adopt the machine instead of the manual welding, i.e., the modern welding from handcraft to scientific manufacturing, intelligentized welding manufacturing (IWM) [1, 6, 7].

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The intelligentized welding manufacturing (IWM) is to simulate intelligent behaviors and functions of the human's sense, brain and body activity in welding process of various manufacturing products by the artificial intelligence (AI) technology about in recent two decades [8–10]. And the IWM undoubtedly is the most representative in the smart/intelligent manufacturing techniques of all modern industries.

Many scholars have explored the application of various AI methods and technologies to intelligentized welding manufacturing processes and systems [11–14], such as that multi-source information sensing technologies such as computer vision, arc sound, spectrum and so on are used to obtain welding process information [8]; the AI algorithms and techniques, such as machine learning and data mining, are used to extracting and modeling of the knowledge in welding process [9]; and various intelligent control methods, such as fuzzy logic, neural network, self-learning and adaptive control, are used to realize intelligent control of welding dynamic process and its complex system [10].

And the combination of various intelligent sensing, information processing, knowledge modeling and control algorithms and methods is integrated into highly complex and intelligent welding systems, such as robotic welding workstations, automatic welding production line and intelligent welding workshop/factory.

In the previous published literature, the intelligent welding technology, the system and the intelligent structure of the intelligentized welding manufacturing workshop are put forward in [6, 7]. References [8, 15–40] show the research of multi-information sensing and fusion algorithm for visual image of welding zone, arc sound, arc spectrum, current and voltage, position track deviation and so on in the welding dynamic process. Many intelligent methods such as data-driven, system identification, fuzzy identification, artificial neural network, support vector machine, rough set, Petri net and multi-agent are presented for welding process and intelligent modeling method of robot welding system and complex welding manufacturing system in [9, 15, 16, 41–53]. References [10, 15, 16, 54–61] show various intelligent control methods, such as classical PID, adaptive, self-learning, neural network, fuzzy control, neural network control, hybrid logic dynamic (MLD), expert control, and their combined or composite control algorithms and methods, for realized intelligent control of weld pool dynamics, weld seam tracking, welding seam forming and complex intelligent welding system.

It is obvious, in the above-mentioned use of various welding process sensing, information processing, knowledge modeling and real-time intelligent control methods and algorithms to achieve results, and the inevitable scientific and technological implementation problems are the combination of these intelligent methods and algorithms based on different theories, different description forms and different implementation methods, i.e.,

How to evaluate the controlled processes and the effects of combination or mixing with various intelligent algorithms and methods?

How to analyze and construct the most reasonable or optimal composite or hybrid intelligent algorithms and methods in order to achieve the optimal control objectives for the controlled object?

The above-mentioned problems are not only the confusion of the hybrid intelligent control method used in the complex intelligent welding system. At the same time, it is also the most challenging problem to realize the disordered application of artificial intelligence technology in a large number of intelligent manufacturing systems.

The second part of this paper will describe the existing general concepts and problems of hybrid intelligence in complex intelligent systems and related research work. The third part of this paper will classify and analyze the intelligent methods and algorithms existing in the intelligent control of welding process and robot welding system. Furthermore, the hybrid intelligence problem in intelligentized welding manufacturing process and system is put forward. In the fourth part of this paper, some examples of hybrid intelligent sensing, modeling and control methods in intelligentized welding manufacturing process and system are presented, and some preliminary analysis results are given. In the last part of this paper, we will discuss the future research direction of hybrid intelligence problem in intelligentized welding manufacturing process and system.

2 Hybrid Intelligence Problems in General Intelligent Systems

Since Minsky, McCarthy and other scholars put forward the concept of artificial intelligence (AI) in the 1950s, the AI has made some epoch-making achievements, for example, with the development and composite application of many AI technologies, such as perceptron, fuzzy set theory, expert system, error backpropagation algorithm, genetic algorithm, particle swarm optimization and so on. Many scholars have noticed that with the combination of various AI methods and the complexity of composite and integrated applications [62–64]. As early as 1991, Minsky, a famous expert in the field of AI, recognized the necessity of studying artificial intelligence systems composed of different intelligent technologies in [65]. Furthermore, in the 1990s, a new research direction in the field of AI, hybrid intelligent system (HIS), has been put forward in [66].

The HIS is an updated research direction with the development of AI, the purpose of which is to make the complicated intelligent system more effective in knowledge representation, reasoning, management and so on [64–80].

2.1 The Preliminary Concept of Hybrid Intelligent Systems

At present, there is no uniform definition on the concept of hybrid intelligent system (HIS) in AI academia [62, 64]. The early definition simply considered the HIS as an integrated system composed of expert system and artificial neural network, or considered that any system with two or more intelligent technologies is a HIS. Later, with the addition of genetic algorithm, evolutionary computation, fuzzy logic, immune algorithm and traditional hard computing technology, the HIS has been developed into a special research direction of AI.

From now on, there are two academic concepts leading the research of hybrid intelligent system. One is "computational intelligence," which focuses on hybrid intelligent systems as a combination of new computational intelligence and traditional artificial intelligence "symbolism" [67]. The other is "intelligent application," which mainly investigates the HIS with integration of "soft computing" and "hard computing" in various AI technologies, that is, so that the problems in reality can be solved better [68].

Therefore, the HIS can be summed up as an intelligent system with integrating at least one intelligent technology and non-intelligent technology for complex practical problems in order to obtain a better knowledge representation, reasoning and problem-solving capabilities, and run robust and more efficient applications.

2.2 Research on Theory of Hybrid Intelligent System

The theoretical research of hybrid intelligent system mainly includes the research motivation, the classification, the construction method, the evaluation criterion of hybrid intelligent system and so on, as follows.

The motivation of hybrid intelligent system

- The idea of hybrid intelligent system is to overcome the deficiency of single technology.
- The hybrid intelligent system is proposed because a single technology cannot solve all the subproblems of practical application problems.
- The hybrid intelligent system uses a hybrid structure to realize the ability of multi-information processing, which is better than the single intelligent technology imitating human intelligence.

The classification of hybrid intelligent system

- According to the structure of the HIS, the HIS is divided into: stand-alone models, transformation models, loose-coupling models, tight-coupling models, fully integrated models [69].
- According to the motivation of the study, the HIS is divided into: function replacing hybrids, intercommunicating hybrids and polymorphic hybrids [70]. This paper analyzes whether these hybrid intelligent systems, which are grouped into one class because of "common reason," have any common ground in the choice of concrete construction methods.
- According to the different fusion forms of "soft computing" and "hard computing," HIS is divided into seven categories: There are mainly isolated, parallel, feedback, cascaded, designed, augmented, assisted [71].

The HIS is classified from the point of view of system theory, especially the input and parameter value of the system are considered. In addition, some papers [72, 73] have studied the classification of the HIS.

The construction method of hybrid intelligent system

The construction method of HIS is one of the most important research fields in HIS. It is not only the most operational part of the methodology of HIS, but also the least studied part of HIS [74]. The main research reports are as follows:

Goonatilake first put forward a six-stage development method of HIS [70]: problem analysis, prototype matching, hybrid category selection, implementation, validation and maintenance. The problem analysis is mainly to determine the sub-task and its attributes, prototype matching is mainly to select the appropriate technology for each sub-task, and the hybrid category selection is to select the type selection of the HIS to be used. The six-stage development method proposed in reference [70] is carried out according to the steps of information system development, which is of great significance to the development of a new HIS.

In recent years, some scholars have proposed a HIS construction method based on agent. According to the dynamic interaction characteristics of agent, Zhang proposed "agent-based hybrid intelligent system framework" [75]. The framework is composed of interactive agent, planning agent, problem-solving agent, synthetic agent, intermediate agent and various technology agents. The most important part is the intermediate agent, which mainly stores the capability of each technology and retrieves the ability according to the demand. Li et al. also proposed a HIS framework based on agent (MAHIS [76]), which consists of eight models: hybrid strategy identification model, organization model, task model, agent model, specialist model, coordination model, etc., reorganize model and design model. The "agent-based hybrid intelligent system framework" can be built independently according to the needs of the task, but the problem of this framework is that it must be described according to the problem to be solved. They are stored in agent in the form of ontology, and problem-solving agent must have knowledge in this field, which is difficult to achieve.

The evaluation criteria of hybrid intelligent system

It is of great significance to determine the evaluation criteria for hybrid intelligent systems to guide the design and construction of hybrid intelligent systems. At present, there is little systematic research in this area, which is basically the evaluation of the results of hybrid intelligent system.

The evaluation criteria proposed by Hefny et al. in [77] include: error level, training process, structural complexity, reasoning capability. Reference [77] also pointed out that with the increase of various technologies used in the mixing process, there may be problems in coupling, structural complexity, learning algorithm and computational complexity of the system.

In the process of studying the industrial data analysis, according to the developing process of the hybrid intelligent system, Kordon put forward the evaluation criterion of the HIS [78]: robustness, speed and cost of the development process; sensitivity to change; self-evaluation of performance; and maintenance costs.

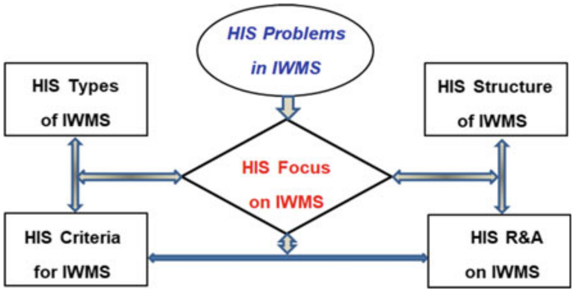


Fig. 1 HIS problems for the IWMS

To sum up, we summarize the research background, motivation content and key problems of general HIS in the following diagram, Fig. 1, including the relationship between the types, structures, criteria and application effects of HIS for the IWMS.

3 Hybrid Intelligence Problems in Intelligentized Welding Manufacturing Systems

3.1 The Intelligent Functions and Structure of IWMT/S

In our previous published literature [1, 6, 7], we have put forward and expounded the conceptual and technical framework of intelligentized welding manufacturing (IWM), intelligentized welding manufacturing technology/system (IWMT/S), intelligentized robotic welding technology/system (IRWT/S), intelligentized welding manufacturing engineering (IWME) and so on. Of course, it is mainly aimed at the most representative arc welding process without losing its generality.

In Ref. [1], the intelligentized welding manufacturing (IWM) is preliminarily defined as for simulating intelligent behaviors and functions of welder's sense, brain and body activity in welding process by the artificial intelligence technology; see Fig. 1 for composition parts of the IWM process. Furthermore, investigating the constitution of general intelligentized manufacturing, functions and systems, we present a pentabasic framework of intelligentized functions in the IWMS, as shown in Fig. 2.

Replacing manual welding with machines, which is also a dream that has been pursued by welding practitioners for thousands of years, Fig. 3, it also is the key technology of the IWM, i.e., IRWT in Fig. 4.

Based on scientific and technical contents related to development of modern welding manufacturing technology, the concept on intelligentized welding manufacturing technology (IWMT) is introduced [1, 6, 7], and it shows for the key scientific and technical formwork of the IWMT, which contains three advanced manufacturing fields: the virtual and digital welding manufacturing and technology (V&DWMT) including the virtual manufacturing; intelligentized robotic welding

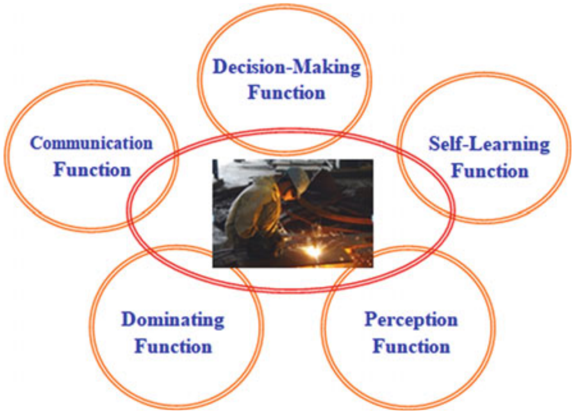


Fig. 2 A pentabasic framework of intelligentized functions in the IWMS

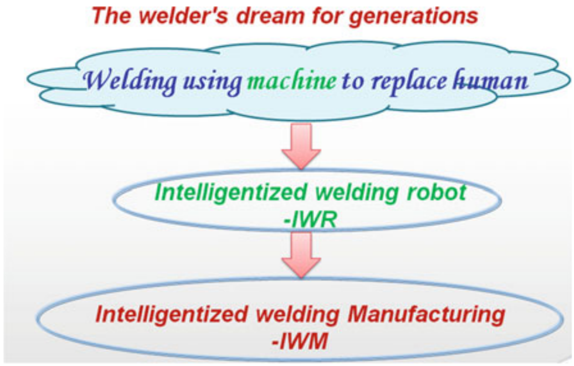


Fig. 3 Welder's dream for generations: IWR to IWM

technology (IRWT) and the flexible and agile welding manufacturing and technology (F&AWMT); and key technical elements and system techniques of the IWMT including the network manufacturing.

In the process and systems of the IWM for the large equipment, a composition of the IWME/T/S is shown in Fig. 4.

For example, in an intelligentized welding manufacturing workshop/factory for major equipment, corresponding to the pentabasic intelligence functions in Fig. 2, it can be summarized as follows: a functional diagram of IWMW's pentabasic framework of the IWMS, as shown in Fig. 5.

The Fig. 5 shows an IWMW construction, its core technology is the IWT and its IWMS, which can be divided into five types of technologies, such as the WT, RT, NT, IT, and DT. And constitute the corresponding five kinds of intelligent systems, such as the MS, FS, DS, IS and VS.

Obviously, in the above-mentioned IWMT/S, it involves the combination or mixed application of a variety of AI techniques and methods.

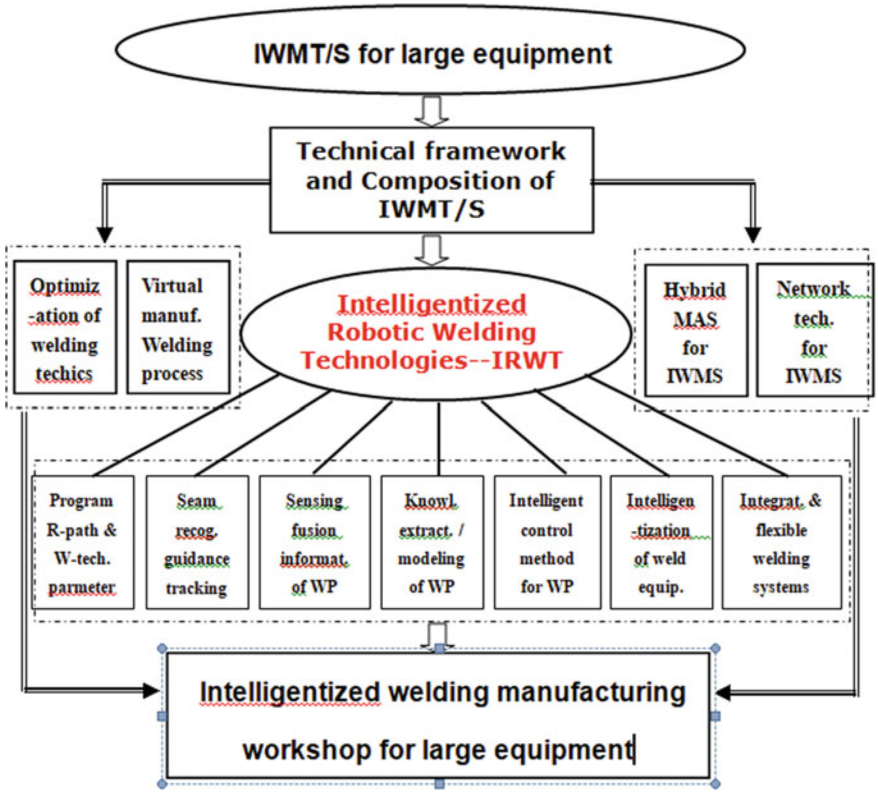


Fig. 4 A composition of IWME/T/S for a large equipment

As one can see, the IWMT/S involves three key elements of intelligentized technology for welding process and systems: sensing welding process for imitating welder's sense organ function, knowledge extraction and modeling of welding process for imitating welder's experience reasoning function and intelligent control of welding process for imitating welder's decision-making operation function.

In the research literature published by us and other scholars, the various AI techniques and methods used in the welding process and system under different conditions are shown, such as the optimal planning of robot welding task, process and its parameters. The AI includes the fuzzy logic, neural networks, expert systems, data mining, knowledge extraction and modeling, machine learning, adaptive and self-learning control algorithms and combination of these different algorithms. In the intelligent welding process, sensing, information processing, feature extraction, knowledge modeling and feedback control methods and algorithms, there are a lot of problems in the analysis and optimization of hybrid intelligence phenomenon and hybrid intelligent action process. In the past, only the sensing of specific processes and systems has been studied. Modeling and control are a very important and practical AI complexity problem that has not attracted attention or been specifically discussed.

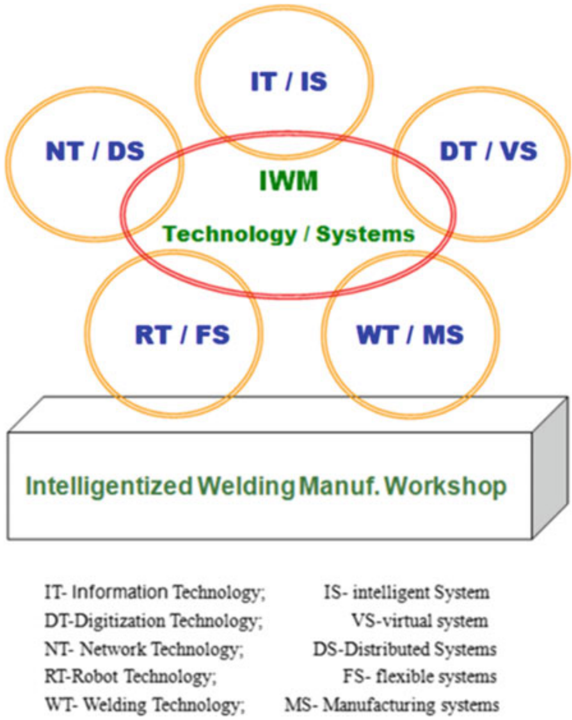


Fig. 5 A pentabasic framework of the IWMW

It is also an unavoidable bottleneck and challenge in the theory and application of hybrid intelligent algorithms and techniques. Therefore, this paper seriously put forward in order to attract scientists and engineers' enough attention on a so-called hybrid intelligence problem in the IWM process and systems.

One can see the following examples of hybrid intelligence in the IWMS.

3.2 Hybrid Intelligence Features of Multi-information Processing and Fusion for Arc Welding Process

HI features of acquisition and processing of multi-source information in GTAW process

In the Refs. [8, 15–40], the multi-information and complexity in arc welding dynamical process are presented in Fig. 6, which includes four categories, such as welding process, arc, vision and motion information, and about 20 kinds of measurable information that occur during welding in Fig. 6.

The experimental system with multiple sensors and acquisition for sensing and acquiring arc, sound, spectrum and other signals in the dynamic process of GTAW established in SJTU's Robot Welding Intelligent Technology Laboratory is shown

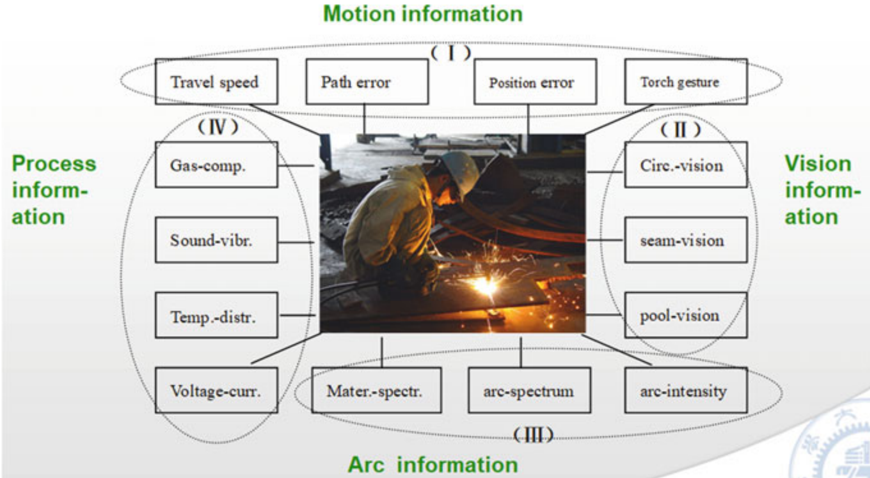


Fig. 6 Multi-information and complexity in arc welding dynamical process

in Fig. 7, which includes vision, sound, spectrum sensors for arc features during the pulsed GTAW. Based on the above experimental system, Fig. 8 shows experimental results of arc voltage, arc sound, spectrum, weld pool image and other signals during the pulsed GTAW dynamic process.

The image information features of the weld pool are also shown in Fig. 8, which are unwelded or under-penetration, as well as burn-through or weld leakage.

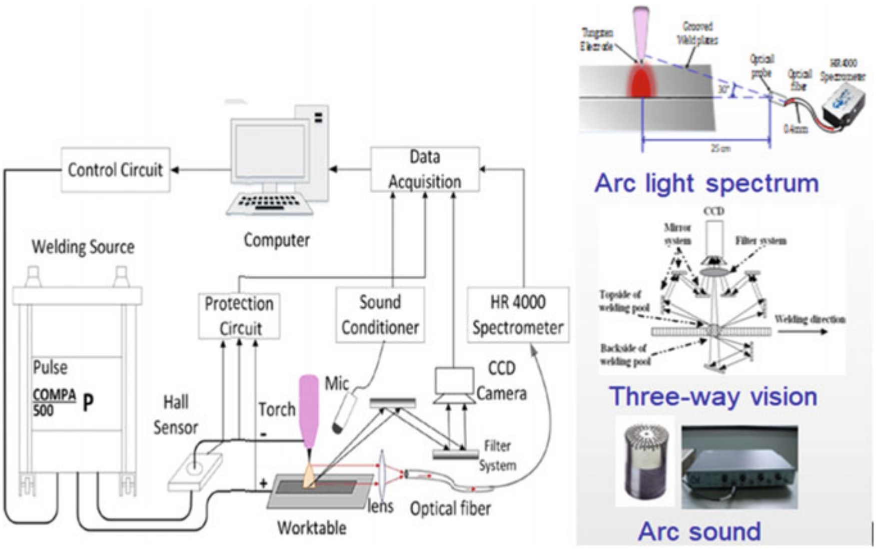
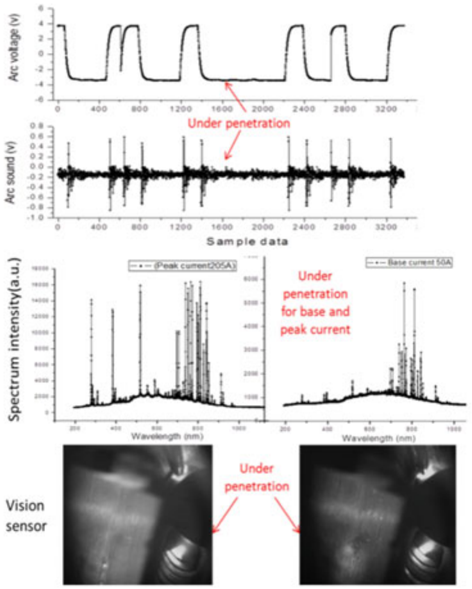
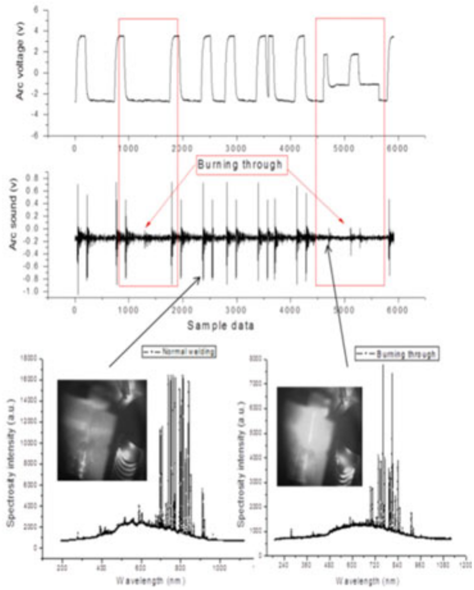


Fig. 7 Multiple signal acquisition systems for pulsed GTAW

Fig. 8 Arc voltage, sound, spectrum and image information during pulsed GTAW



(a) Defect of under penetration



(b) Defect of burning through

Among these methods to process the multi-information features, there are many different intelligent computing methods and their hybrid application. The mixed effect of hybrid intelligent processing algorithms is obviously a very important problem, and it is needed for further analysis and investigation.

HI features of multi-information fusion algorithms for predicting welding penetration in GTAW dynamical process
In Refs. [9, 26–28, 40], the method and algorithm of multi-source information fusion in welding process are studied and discussed. Based on the information of arc voltage, visual image and arc sound in GTAW process, intelligent processing algorithm is used to extract penetration features, and then multi-information feature layer fusion method and neural network and DS evidence algorithm are used to predict welding penetration.

HI features of multi-information fusion for arc welding dynamical process
Summarized our research and current literature [9, 26–28, 40], a variety of intelligent processing algorithm and multi-information fusion methods and their algorithms are used in the welding dynamic process for monitoring and quality prediction of welding process, and the combination of various intelligent algorithms or hybrid features can be seen in the following illustration; i.e., various combined or hybrid intelligent algorithms have been widely used in multi-source information fusion algorithms, such as sensing, feature extraction, classification and prediction for welding dynamic process, shown in Fig. 9.

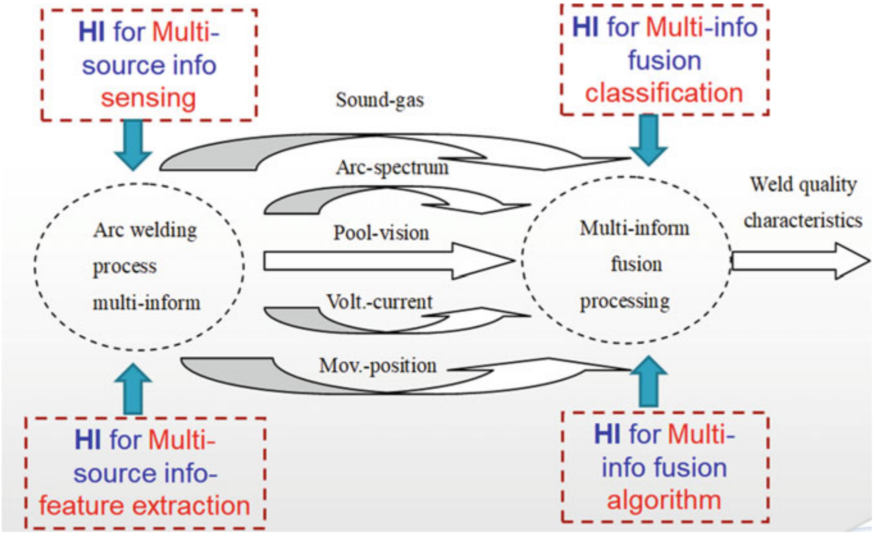


Fig. 9 HI features of multi-information acquisition and processing of arc welding process

3.3 Hybrid Intelligence Features in Intelligent Modeling Methodology for Welding Dynamic Process

In the literature on modeling method of welding dynamic process [9, 15, 16, 41–53], several typical methods and algorithms of intelligent modeling for welding process can be summarized as shown in Fig. 10.

The intelligent modeling methods for welding dynamic process are given as follows:

- Knowledge modeling class: including expert system, fuzzy logic, empirical rules, rough set, identification modeling and so on;
- Artificial neural network (ANN) modeling class: including support vector machine, genetic algorithm, ant colony algorithm and other methods;
- Multi-agent, hybrid logic dynamics, various programming and optimization algorithm modeling methods, etc.;
- The combination of modeling methods and algorithms of various intelligent algorithms mentioned above.

Neural network prediction model for characteristics of welding pool. The neural network (NN) method has been applied to the modeling of welding process for nearly 30 years [9, 15, 16]. The typical NN model is suitable for predicting the dynamic process characteristics of welding pool, for example, the prediction of the back pool size and penetration by NN model, which is very important in the closed-loop control of penetration during welding process. There are other welding seam forming, welding quality evaluation using NN model prediction and classification, etc.

Knowledge modeling of welding dynamic process. One of the key intelligent technologies is to establish knowledge model from extracting welder manipulations so that the computer or robotic systems could play back human knowledge and intelligent decision-making function.

Because the differences of human describing himself experience capability and uncertainty in welding process, it is very difficult or almost impossible for one to

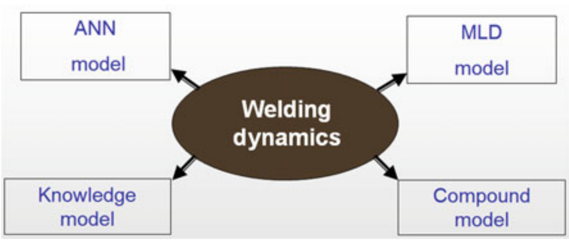


Fig. 10 HI features in intelligent modeling methodology for welding dynamic process

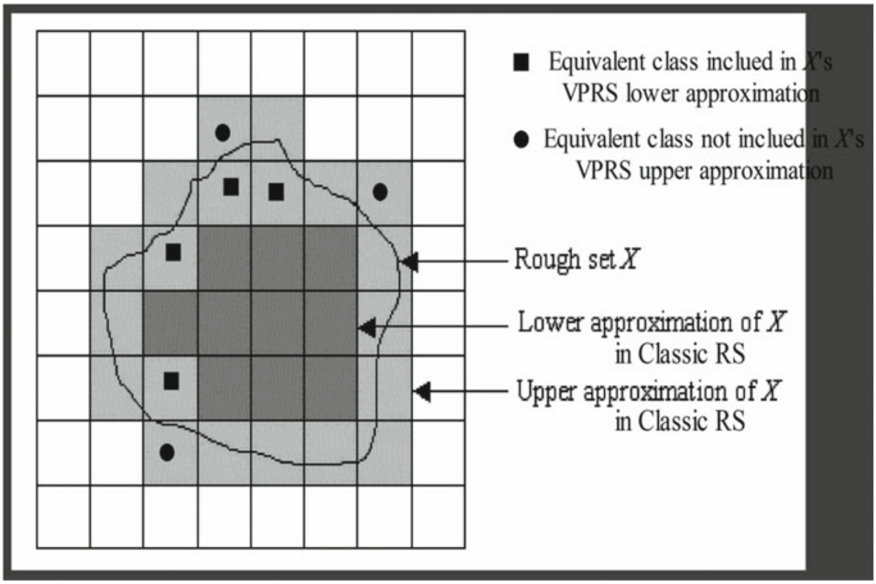


Fig. 11 Rough set (RS) theory for knowledge modeling methods for welding process

directly get enough expert knowledge from welder's experiences [41–47]. A feasible way is extracting knowledge from measured experimental data by fuzzy computing, rough set theory and other soft computing methods. A fuzzy rule model of weld pool dynamics in the pulsed GTAW process was developed by fuzzy identification algorithms in Refs. [42–45]. Knowledge modeling methods for welding process from collected data were investigated by the basic rough set (RS) theory as shown in Fig. 11.

Mixed Logical Dynamical (MLD) modeling of GTAW dynamics during robotic welding.

In the research direction of control theory in the last 20 years, a hot topic is the so-called mixed logical dynamical (MLD) modeling and control method for the complex system, which is useful to model and control the so-called hybrid systems with interacting physical laws, logical rules, continuous and discrete variables, and operating constraints. References [48–52] develop MLD modeling methodology for pulsed GTAW process in robotic welding systems and robotic welding process and systems, which shows the MLD method is highly suitable for welding dynamical process, particularly, automatic and robotic welding systems.

Figure 12 shows the weld pool with misalignment-mixed logical dynamical (WPM-MLD) model and the weld pool with gap-mixed logical dynamical (WPG-MLD) model for estimating the backside weld width [48–50].

And Fig. 13 shows mixed logical dynamical (MLD) modeling of GTAW dynamics during robotic welding, the welding robot movement process (WRMP)-MLD model

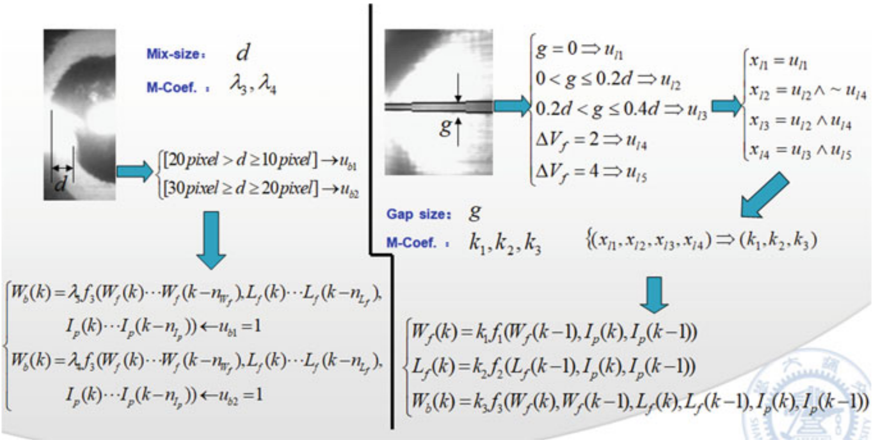


Fig. 12 **WPM-MLD** model and **WPG-MLD** model

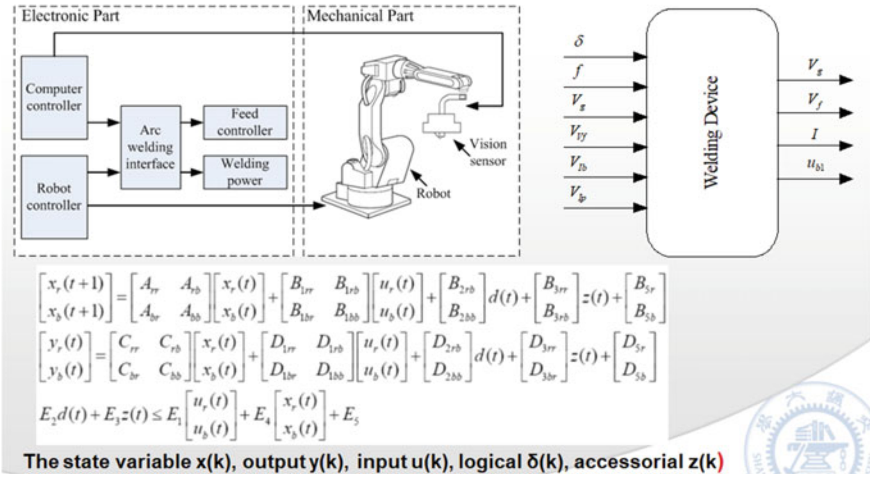
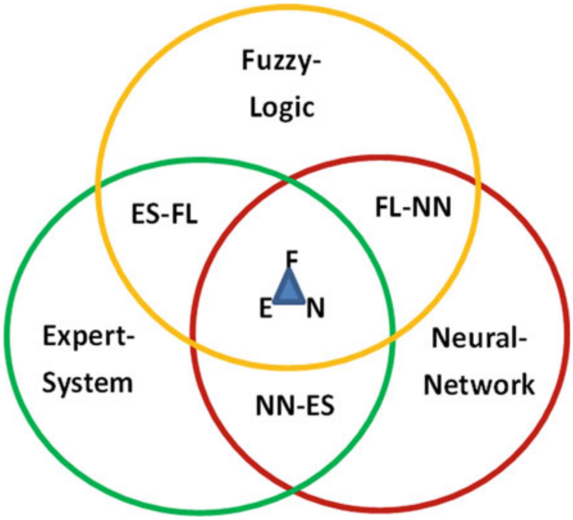


Fig. 13 WRMP-MLD model and WDOP-MLD model for robotic welding process and system

with 34 equations and the welding device operation (WDOP)-MLD model with 65 equations [48, 52].

HI modeling of expert systems, fuzzy logic and artificial neural networks. The most common modeling methods, such as expert system (ES), fuzzy logic (FL) and neural network (NN), are the most common methods in the modeling of welding dynamic process. A single intelligent method or algorithm is represented in a monochromatic outer circle in Fig. 14.

Fig. 14 Interaction of FL-NN-ES intelligent modeling methods



In Refs. [10, 15, 16, 42–47], the knowledge model obtained by using FL, NN and ES modeling methods to the welding dynamic process is presented, respectively.

As shown in Fig. 14, there are two overlapping circles in the middle layer, such as the FL-NN, NN-ES and ES-FL, which represents a composite indication of two intelligent methods or algorithms.

The central part in Fig. 14 is the overlapping part of the three circles, i.e., N-F-E, which represents a composite representation of all three intelligent methods or algorithms.

Furthermore, the hybrid knowledge model of cross and combination of the FL, NN and ES methods for welding dynamic process is developed in Refs. [10, 16].

The interaction of these three intelligent modeling methods is shown in Fig. 14.

Other HI complexity of multi-interaction with intelligent modeling methods and algorithms can be further analyzed and investigated.

3.4 Hybrid Intelligence Features—Intelligent Control Methodology for Welding Dynamic Process

Intelligent control strategy is mainly aiming at complex uncertainty of welding process. Because of especial complexity in welding dynamical process, such as strong nonlinear and multivariable coupling, time–variety and uncertainty, it is specially suitable to adopt intelligent control strategy for welding process and systems [1, 6–10]. At present, various intelligent control methods, fuzzy logic, artificial neural networks, expert system and their combination control schemes [11–16, 55–61, 81–85], are shown in Fig. 15.

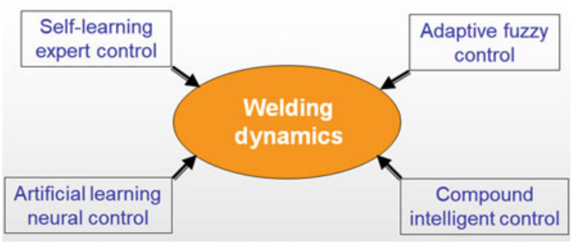


Fig. 15 Intelligent control methods in the welding process

According to different welding conditions, such as based on plate welding, butt welding, with filler, gap variety and uncertainty in welding process, many intelligent control methods, such as a self-learning expert control, fuzzy neural control, adaptive fuzzy neural control, compound intelligent controller with feed-forward compensating control methods for gap variety [59] and so on, have been developed for the penetration, the width of the upside and backside pool and seam, face reinforcement and fine forming of the weld seam during arc welding process.

The expert system for real-time control of welding process is an important part in intelligentized welding systems. Some advanced autonomous expert system for control of welding dynamical process should be still investigated for mode recognition of weld workpiece, environment and seam type, and autonomous programming robotic welding path and techniques, intelligent control of welding process in the IWMT [1, 10, 59, 85].

Because various intelligent methods and algorithms act on welding dynamic process and welding equipment system at the same time, for example, robot welding system, the special hybrid intelligent characteristics of welding process and system control are shown in Fig. 16.

The diagram shows the HI characteristics of various methods and algorithms of intelligent information extraction, such as the MSS, MSIF in the HIS, the HIM and IPM in the HIIF for modeling, and control methods and algorithms, such as the KRC, ILC and ESC in the HIC of the dotted box.

In Fig. 17, the characteristics in hybrid intelligent control of robotic welding process and systems, the diagram shows the HI characteristics of various methods and algorithms for the HKT including ER, EK and AP; the HICT including AG, WT and MC; the HIT including MS, MIF and PM; and the HDIT including ICSM and NC, which are circled in the red dotted box in the diagram [1, 81–84, 86–98].

4 HI Features in Application on the IWMS/W/F

The previous section discusses the complex, mixed or hybrid intelligence characteristics that are shown in the combination of various intelligent methods used in IWM technology and methodology with the various AI algorithms.

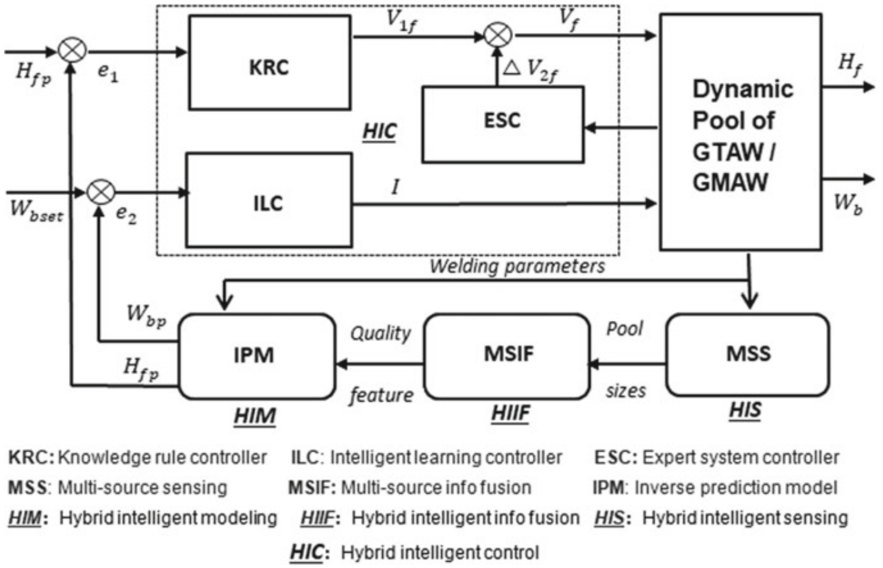


Fig. 16 HI features in intelligent control of arc welding process

The next section will discuss the hybrid intelligence features of multiple intelligent methods and AI algorithms shown in IWM engineering applications, such as the IWMS (systems)/W (workshop)/F (factory).

4.1 Hybrid Intelligence in IWMS/W/F by Internet of Things

With the application of the Internet of things technology in the industrial field, it has effectively promoted the innovation and development of intelligent manufacturing technology and system based on the Internet of things. We also propose an Internet of things-based IWMT/S in the welding field as shown in Fig. 18 for design and structure of IWM workshop and factory. The part of the red dashed frame in Fig. 18 includes a variety of intelligent welding methods based on the Internet of things technology and the system of AI algorithm in the application of in intelligentized welding manufacturing engineering (IWME), such as the hybrid intelligent methods and algorithms displayed in MES level and intelligent control level of the intelligentized welding manufacturing workshop by Internet of things (IWMWIT) in Fig. 18.

The optimal planning method and algorithm for welding product task, such as robotic welding path, attitude and welding process parameter planning, expert system of welding process, visual recognition method and algorithm for welding initial point; The autonomous guidance and tracking control method and algorithm in robotic

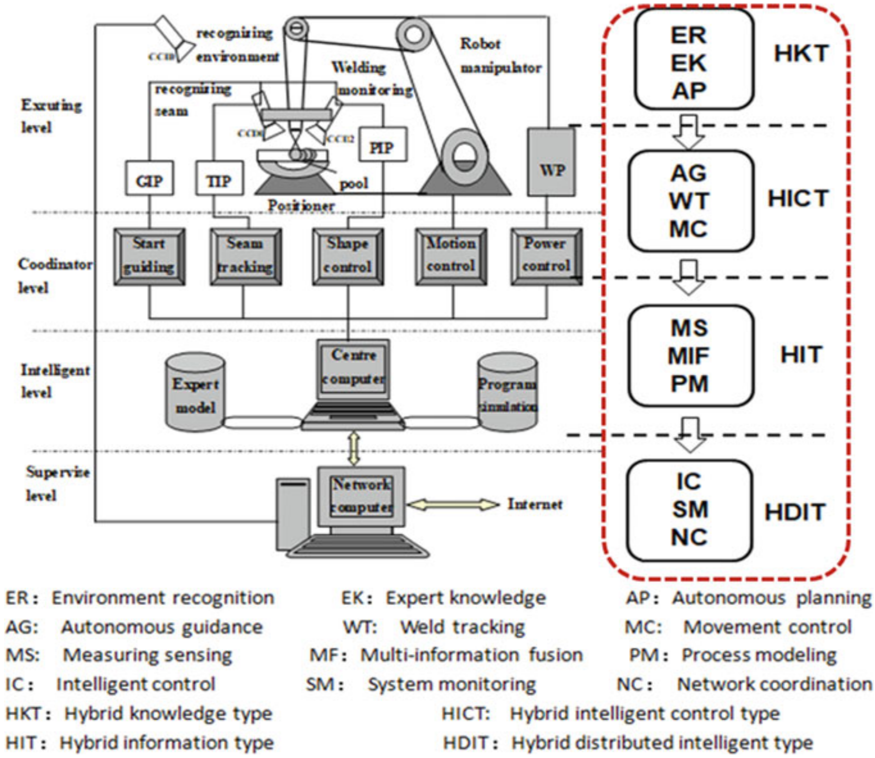


Fig. 17 HI features in intelligent control of robotic welding process and systems

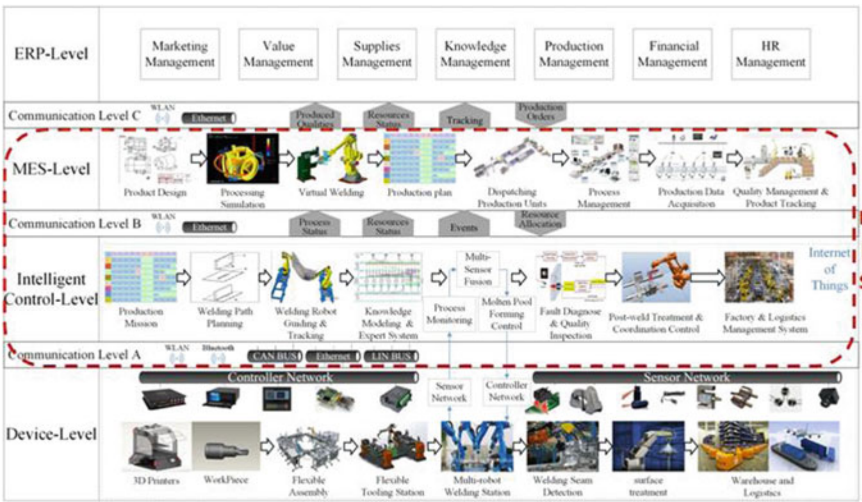


Fig. 18 HI features displayed in application of the IWM **workshop** by Internet of things

welding process, such as acquisition and processing of multi-source sensing information such as vision, arc, sound and spectrum in the process of welding, and the technology and algorithm of multi-source sensing information acquisition and processing in the process of welding; The Data driven expert system for monitoring of welding process; The knowledge model and penetration prediction model; The intelligent control method and algorithm of weld pool penetration and weld forming, prediction algorithm of welding quality; The fault diagnosis of welding process and system; The communication and coordination control of welding production line and workshop equipment, and the intelligent management of the whole process of welding product manufacturing, all of which highlight the complexity of hybrid intelligent technology features in the IWMWIT, are shown as the red dashed frame HIS in Fig. 18.

4.2 A Multi-agent Hybrid Intelligence Structure for IWMS

A hierarchical MAS coordinated control structure of intelligentized welding manufacturing system (IWMS) is proposed in this paper. The IWMS is designed as so-called a multi-robot device follower and a network virtual leader for the IWMS [99, 100]. It is a hierarchical multi-agent system; i.e., the IWMS is divided into "leader MAS" and "follower MAS" and "bottom follower MAS" structure with multi-intelligent cooperative operation. It implements the "total goal coordination" and "sub-task coordination" two-level MAS coordination mechanism of the IWMS. The "leader MAS" in the first layer of the IWMS completes the "goal coordination" (LMAS-0) of multiple MAS. The first layer of multiple "follower MAS" (FMAS-1i) is the control of sub-task coordination (LMAS-2i), which is the leader of the second layer of multiple MAS. The sub-task coordination (MAS-2i) of multiple MAS leaders in the second layer is directly controlled by root task coordination of multiple agent (F-agent-3-ij) execution units. This paper proposes the "leadership-follow" mechanism for the MAS hierarchical network coordination control structure diagram shown in Fig. 19, which contains the complex HIS characteristics of multi-agents and IWMT/S.

For the design and implementation of hybrid intelligent system of MAS and IWMT/S, this paper presents a structure diagram of a hybrid intelligent system of welding manufacturing (HISWM) shown in Fig. 20, which contains the different classifications of MAS and various intelligent methods and algorithms.

4.3 An Intelligentized Welding Manufacturing Workshop for Offshore Drilling Platform

As one of the application practices of the IWMT, our research team and Shanghai ZMPC have developed a kind of intelligentized welding manufacturing workshop

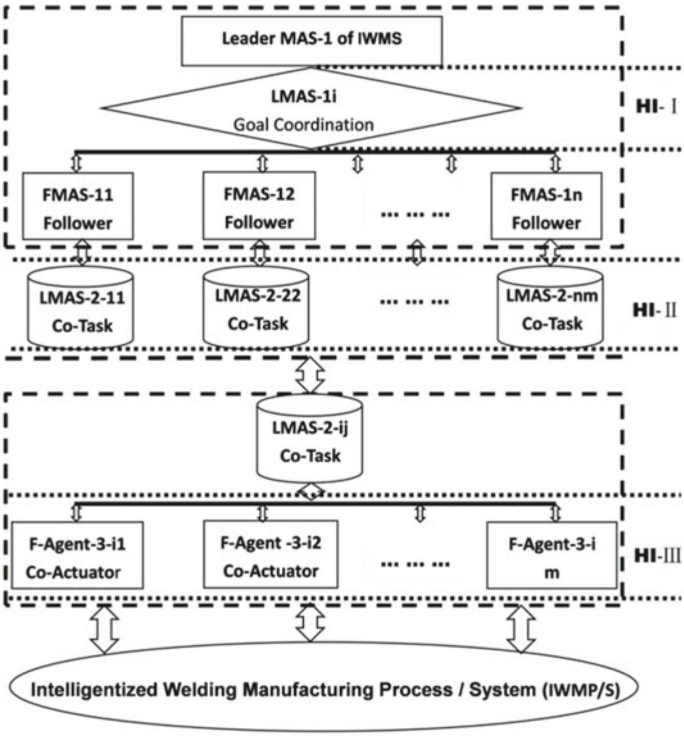


Fig. 19 Leader–follower MA—HI structure of the IWMP/S

(IWMW) for the pile legs of the offshore drilling platform as shown in Fig. 21. In this IWMW, the IWMS technology has been successfully applied to the construction of the IWMW for supporting the pile legs of the offshore drilling platform. The intelligent welding technology, production system and product quality and benefit of offshore drilling platform are greatly improved.

The IWMW for piles and legs of the offshore platform reflects the pentabasic structure function of the IWMT proposed in this paper, as shown in Fig. 22. On the basis of the general intelligent manufacturing system, it shows the key technology in the robotic welding flexible system, as well as the information, digitalization, networking and intelligentized manufacturing technologies in Fig. 22, combined with the welding process requirement of the pile leg of the offshore platform, the IWMW for piles and legs of the offshore platform is integrated and implemented.

Furthermore, the intelligent pentabasic technology, systems and methodology of the IWMW for the pile legs of the offshore drilling platform and the hybrid intelligent function of the IWMW can be analyzed accordingly, as shown in Fig. 23.

It shows the hybrid pentabasic intelligent function of IWMW for the pile legs of the drilling platform, which can be divided into the single intelligent tech./syst. in outer layer, such as IT/IS, DT/VS, WT/MS, RT/FS and NT/DS; the triple intelligent

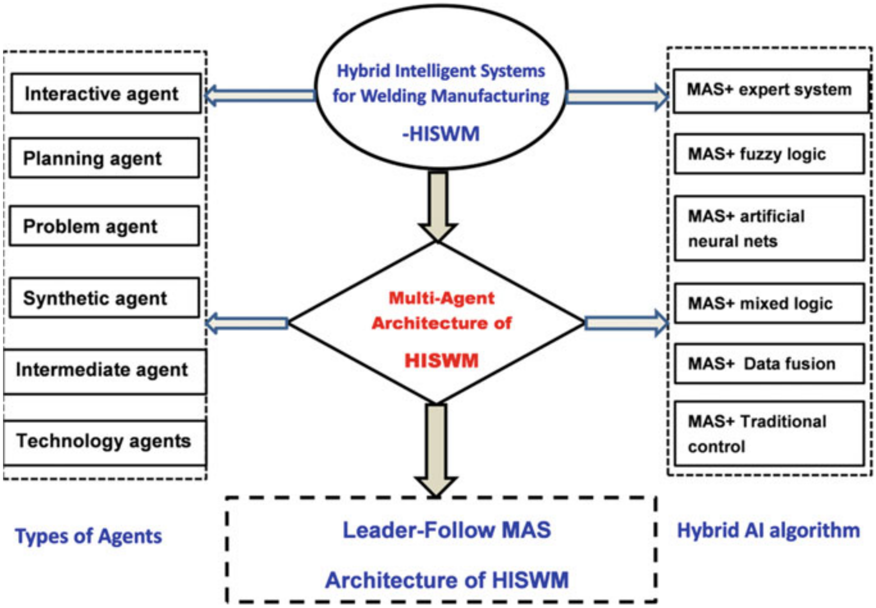


Fig. 20 A hybrid intelligent system of welding manufacturing (HISWM)

recombination in the middle layer, such as I/D/R, D/W/N, W/R/I, R/N/D and N/I/W tech./syst.; and the quintuple or hybrid intelligence phenomena I/W/D/R/N tech./syst. in the core, as shown in Fig. 23. Further, hybrid intelligence features are related to different AI methods and algorithms used in practice.

5 Concluding Remarks

This paper presents some hybrid intelligence problems and the HI features in IWMT/S/W/F. Based on the technological constitution of the IWMT/S, the paper investigates the hybrid or compound, multiple and mixed effects of different intelligent methods and technologies applied in IWMT/S, which includes the hybrid intelligence problems existing in multi-information sensing, knowledge modeling of arc welding process and intelligent control methodology for welding dynamic process, and the hybrid intelligence problems existing in intelligentized technologies for robotic welding process and systems. The HI problems in the IWMT/S are also an unavoidable bottleneck and challenge in the theory and application of hybrid intelligent algorithms and techniques. Therefore, this paper put forward the HIS problems in the IWM process and systems in order to attract scientists and engineers' enough attention on that.

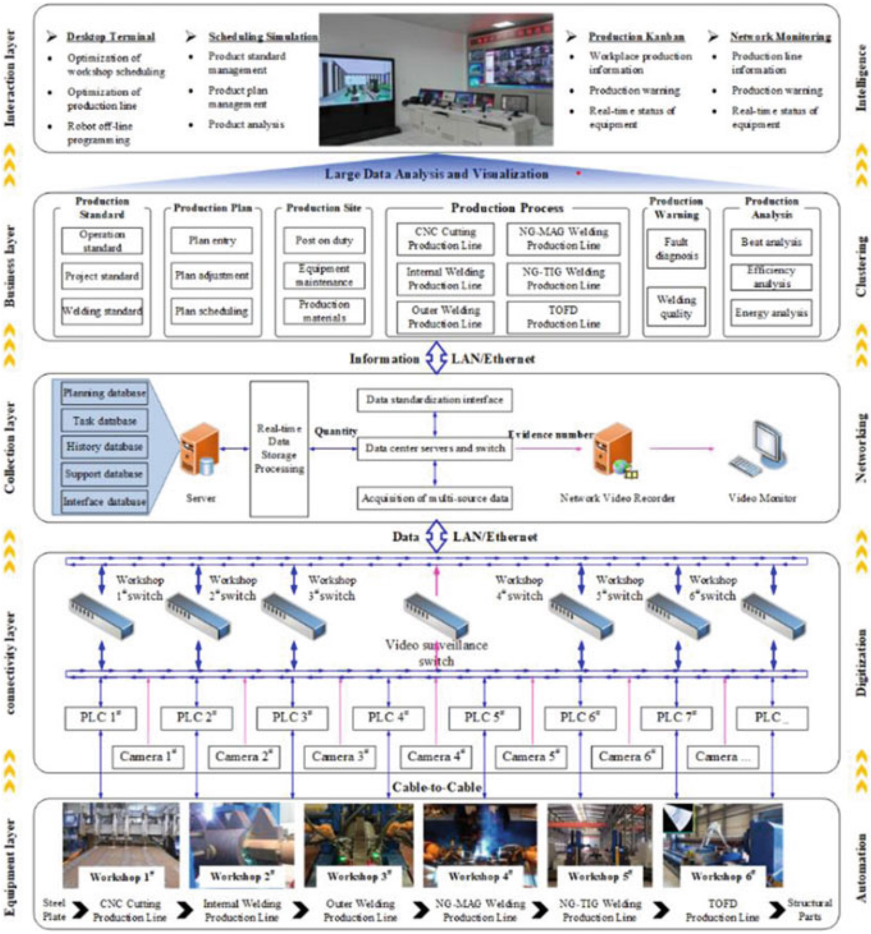


Fig. 21 A realization of the IWMW for the pile legs of the offshore drilling platform

The author hopes to further explore the optimization methods of hybrid or composite intelligent algorithms of IWMT/S by putting forward the problems of the HI methods and techniques existing in IWMT/S, and the optimization design of the HIS of the IWMS and IWME.

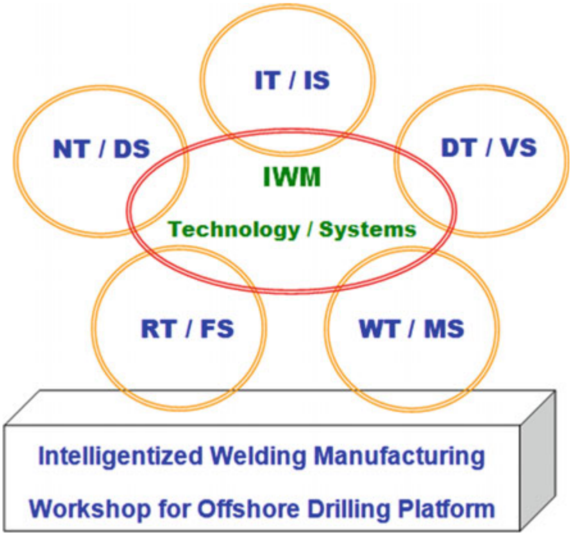


Fig. 22 Pentabasic function of the IWMW for piles and legs of the offshore platform

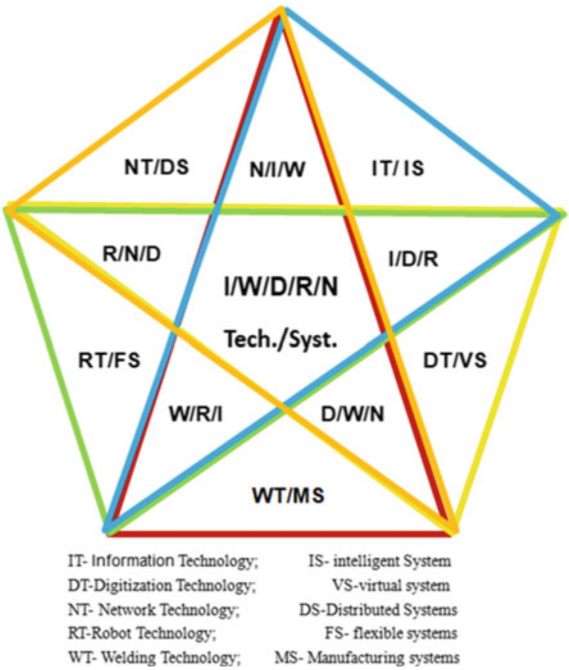


Fig. 23 Hybrid intelligent function of the IWMW for the offshore drilling platform

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