On Intelligentized Welding Manufacturing.pdf

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Abstract This paper presents some concepts on intelligentized welding manufacturing, such as the ideas of intelligentized welding manufacturing technology/systems (IWMT/S), intelligentized robotic welding technology/systems (IRWT/S) and intelligentized welding manufacturing engineering (IWME), and investigates the framework and constitution of technologies and systems for intelligentized welding manufacturing. Furthermore, the paper also shows some new evolutions of research works in the IRWTL at SJTU on intelligentized welding manufacturing, which includes multi-information sensing and knowledge modeling of arc welding process; intelligent control methodology for welding dynamic process; intelligentized technologies for robotic welding and intelligentized autonomous welding robot system for the special environment. The author wishes to present a systematization of intending research framework and constitution on the IWMT/S in this paper. Some studies on intelligentized welding presented in this paper might introduce related essential research directions or fields of intelligentized technologies for modern welding manufacturing.

1 Introduction

With development of modern manufacturing, the intelligent manufacturing (IM), which is to simulate intelligent behaviors and functions of the human’s sense, brain and body activity in manufacturing process of various industrial products by the Artificial Intelligence (AI) technology, is increasingly becoming an inevitable trend about in recent two decades [1–7], and the intelligentized welding manufacturing (IWM) undoubtedly is the most representative intelligent manufacturing in all IM processes.
As is known to all, welding handicraft was invented more than 3000 years, and traditional welding was implemented mainly by welder handwork and experiences. Manual welding operation is not only a burdensome and tedious labor for welder; moreover, reliability and consistency of welding quality depends on welder’s skills and experiences, but efficiency of welding production is also limited strictly [1–3].

Studying and simulating intelligent action and function of welder’ operations is very significant for the development of intelligented robotic welding [4]. Much better than any welding robot, a professional welder is highly adaptive to practical situations through observing the position of welding joint, pool dynamics and appearance of the welding seam to identify the welding status; and regulating the parameters to produce high quality welding seam [5–7]. To realize automatic welding similar to welder, three essential technical approach are inevitable, the first is to sense and acquire information of the welding process in real time, similar to human sensing organs for detecting the interior and exterior welding conditions; the next is to identify characteristics of the welding process, i.e. modeling the welding process; the third is to develop the human-brain-like controller to reason the controlling strategy [8–10].

With requirements of modern welding manufacturing, it is become an inevitable trend to realize automatic, robotic, flexible and intelligented welding technologies [11–14]. Modern welding manufacturing has developed and evolved from the original handworked craft to the modern systemic technical science, and it is related to material, mechanical, electrical, control, computer sciences and other extensive subject technical fields. As far as easing welder works, one of main functions in modern welding manufacturing systems is to substitute or partially replace the physical force and brains doings of a welder with machines. It is one of hot topics in advanced welding manufacturing technologies to simulate and realize a welder’s actions by some intelligent machines [12].

Aiming at the bottleneck technological problem of effective control of weld quality during automatic and robotic arc welding process, this paper will present mainly researching works on intelligented methodology for arc welding dynamical process in the Intelligented Robotic Welding Technology Laboratory (IRWTL), Shanghai Jiao Tong University (SJTU), which involves multi-information sensing and feature acquiring, knowledge modeling and intelligent control of arc welding dynamical process [11, 12].

Since arc welding is one of the most representative welding techniques with wide application in modern welding manufacturing, no loss of generality, this paper discusses main intelligented technical problems related to intelligented welding manufacturing technology/systems (IWMT/S), intelligented robotic welding technology/systems (IRWT/S) and intelligented welding manufacturing engineering (IWME) combining with an arc welding technics, which could be also useful to other welding techniques.
2 The Concepts, Frameworks and Constitutions of the IWMT/S

In this paper, 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, seeing 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 the IWMS as Fig. 2.

Based on scientific and technical contents related to development of modern welding manufacturing technology [11–14], the concept on intelligentized welding manufacturing technology (WMT) as Fig. 3 is introduced in this paper, 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 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.

The IWMT is mainly related to key intelligent technical elements: 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. Figure 4 shows some key scientific methods and technologies of the IWM.

![Fig. 1 Composition of IWM](image-url)
Fig. 2  A pentabasic framework of IWM

Fig. 3  The framework of the IWMT
3 Intelligentized Welding Technologies and Systems

3.1 Multi-information Acquisition of Arc Welding Dynamical Process

As it is well known, monitoring and sensing of arc welding dynamic process is very important for real-time control of welding manufacturing process [15–18]. The arc welding dynamic process is extremely perplexing, which contains plentiful, complicated and uncertainty information during welding process. Many sensing methods for arc welding process have been used in consideration of the disturbance from arc, high temperature, vibration, electromagnetic fields and the features of the process, such as ultrasonic for penetration [16], arc pressure method and arc light for vibration information of the weld pool, infrared thermoscope for welding temperature field, X-ray for shape of welding pool [17], acoustic [18] and visual sensing [19–25] for penetration and seam, and so on.

In order to obtain the effectual characteristics of arc welding process for real-time control of weld quality, various signal processing methods have been used for information of arc welding process, such as processing algorithms for arc voltage, current, pool, acoustic, visual, spectrum, thermic, optical, mechanical informations [11]. Figure 5 is a schematic diagram of multi-information sources during arc welding dynamical process. In recent years, the multi-information fusion methods has been also introduced into extraction of characteristics of welding process [26, 27]. Figure 6 is a scheme of multi-information fusion for arc welding dynamical process, and further investigating research on has been developed in [28, 29].
3.1.1 Visual Sensing and Monitoring of Weld Pool Dynamical Process

Vision is one of main functions of human sensing environment information. In manual welding process, the welder receives visual information from weld circumstance, especially weld pool region, and then proper operations are adopted for controlling good welding quality. Therefore, using the computer visual technology to realize human vision and image processing functions in welding process is one of the most important and basic technologies for the IWMT. With development of computer vision technology, using upside pool visual images to detect dynamical varieties of weld pool geometry figure and to predict weld fusing depth, penetration and seam forming has become a hot researching direction [19–24].

In the recent two decades research, we have developed the methodology of visual monitoring and processing of welding pool image [10, 11]. Recently, we...
have presented a visual attention modeling method based on the characteristics of images obtained from the experiments, processed only the region of interest (ROI) [30–32]. The visual characteristics of the pool are effectively extracted and fused to obtain the ROI parameters of the welding dynamic process, and established a flowchart of related image processing algorithms. Since only a small visual attention is processed using the visual attention method, the ROI algorithms of the image processing are used to detect some welding defects occurring during the welding process, such as the feature characteristics of non-penetration, weld leak porosity, slag, and linear misalignment pool images. Figure 7 shows an image processing of a general Al alloy GTAW pool by the ROI detection [31], and Fig. 8 shows an image processing of Al alloy GTAW pool in the three-path images with linear misalignment by the ROI detection in real-time [32].

Compared with other sensing methods, the visual sensing is the most prospective sensing technology since it is not in tough with the welding circuit and workpiece, thus visual signal detection does not affect the welding process so that the visual sensing can provide with sufficient information, such as type of joint, welding edges, type of arc, position of wire and the shape of solidified welding seam.

### 3.1.2 Audio Sensing and Characteristic Extraction of Arc Sound Information

Some investigations show that the arc sound signal is an important information for monitoring of welding dynamics and quality characteristics [33–35], which show

![Image processing of a general GTAW pool by ROI detection](image1)

**Fig. 7** Image processing of a general GTAW pool by ROI detection. a The original, b re-processing, c ROI detection, d ROI processing, e final results

![Image processing of Al alloy GTAW weld pool with linear misalignment by ROI detection](image2)

**Fig. 8** Image processing of Al alloy GTAW weld pool with linear misalignment by ROI detection. a The original, b re-processing, c ROI detection, d ROI processing, e final results
that the arc sound intensity is used as the variable reflecting changes of welding status. The time domain, frequency domain and wavelet features were extracted at different frequency band under different penetration states like partial penetration, full penetration and excessive penetration. Figure 9 shows different features of weld penetration states [36]. Also some other algorithms were developed for extraction of welding status, e.g. penetration characteristics in [35–37].

The Hidden Markov Model with the wavelet analysis algorithms was developed for predicting different penetration status based on all the features of arc sound signal. Figure 10 shows the prediction results of weld penetration based on arc sound features by the Hidden Markov Model and wavelet model. The features of arc sound signal in time domain and frequency domain are essential factors for setting up a predication model of welding quality control. Further investigations are shown in [37].

3.1.3 Spectrum Characteristic Extraction of Welding Dynamical Process

Arc plasma transfers energy from power source to the work-piece and emits large amount of spectra to the surrounding space [38]. The arc spectra contains the abundant information related to welding dynamic characteristics and quality status. The arc spectra during Al Mg alloy pulsed GTAW have been acquired and investigated [39–42]. Some arc spectra processing algorithms were developed for characteristic signals extraction from the original spectral information. The relationships among these extracted signals and the defects caused by wire feed have

Fig. 9 The penetration features of arc sound signals. a dumbbell plate, b trapezoid plate
**Fig. 10** Prediction penetration based on arc sound features by Wavelet and Hidden Markov models. 

- **a** The schematic diagram of recognition model,
- **b** a prediction results of weld penetration

**Fig. 11** Spectral characteristic signals of seam with porosities. 

- **a** Welding seam with porosities,
- **b** *I*/*I*/*Ar* profile as well as the base and the peak profiles
been studied. Figure 11 shows spectral characteristic signals of the seam with porosities \[39, 40\]. The defects of seam oxidation are produced by different disturbances, i.e., the oil painted on the surface of the plate and the non-removed insoluble oxide film of aluminum alloy. And Fig. 12 is the processing procedure of spectral characteristic signals extraction of arc welding \[41, 42\].

### 3.1.4 Multi-information Acquisition and Fusion Extraction of Characteristics During Arc Welding Process

Reference \[26\] developed the experimental system with multi-sensor for acquisition of multi-information of welding dynamical process, combining the three collecting modules, weld pool image, welding current, arc voltage, welding sound and spectral features could be collected at the same time. Figure 13 shows the collected weld pool, current, voltage and sound information in five pulses. From the current, voltage and sound waveforms, it is apparent that the welding process can be divided into weld pulse peak period and weld pulse base period.

The multi-sensor fusion model of the three sensors is developed in \[27\]. The information obtained from each of the sensors was first processed by back-propagation (BP) neural networks individually. Because welding process was influenced by heat inertia, responded to welding parameters with a time delay, the historical information should also be included to obtain more precise prediction results for the back-side bead width. The D-S evidence theory was used to combine the BPAs and obtain the final fusion BPA and obtain the prediction results \[28\], as Fig. 14.

The experiment and analysis results shows that the multi-sensors could obtain better results than a single sensor. The prediction results by fusing three sensors are better than that by fusing two sensors. It shows that multi-sensor information fusion could obtain more information about the welding process and therefore describe the process more roundly and precisely \[26–29\].

![Fig. 12 Procedure of spectral characteristic signals extraction of arc welding](image-url)
3.2 Modeling of Welding Dynamical Process

Another function of welder’s brainpower behaviors is to estimate and manage welding process, it requires welder to be able to understand welding process, handle experience knowledge and make inference and judgement for manipulating welding process [10, 11]. As one of intelligent technical elements, developing model of welding process by maths and knowledge methods is an essential technology for the IWMT. Such as identification modeling method [8–11, 43, 44] by modern control theory, artificial neural network (ANN) modeling [8–10, 45] and knowledge modeling methods [46–51] are used to welding pool process.
3.2.1 Identification of the Non-linear Hammerstein Model of Welding Dynamic Process

We investigate the dynamical characteristics of arc welding dynamic process, and presented and developed a non-linear dynamical model structure for describing heat resource of welding arc as a static nonlinearity and heat conduction as a linear dynamics, i.e., so-called the non-linear Hammerstein model (Ham) for arc welding dynamic process. Figure 15a gives a model schematic diagram of the arc welding dynamic process [43]. The further study developed a MIMO non-linear Ham model for Al alloy GTAW dynamic process [44], shown as Fig. 15b.

3.2.2 Knowledge Modeling of Welding Dynamic Process

Intelligentized welding requires knowledge description of human welding manipulating experiences. One of 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 of the differences of human describing himself experience capability and uncertainty in welding process, it is very difficult or almost impossible for one to directly get enough expert knowledge from welder’s experiences [46–51]. A feasible way is extracting knowledge from measured experimental data by fuzzy computing, rough set theory and other soft-computing methods. References [8, 9] obtains a fuzzy rule model of weld pool dynamics in the pulsed GTAW process by fuzzy identification algorithms. Refs. [46, 47] investigated knowledge modeling methods for welding process from collected data by the basic rough set (RS) theory. Refs. [48, 49] developed an improved knowledge model for Al alloy pulsed GTAW
process by the variable precision rough set (VPRS) theory. Figure 16 shows a principle of the VPRS theory and the schematic diagram of modeling welding process by the VPRS method. Furthermore, we have developed the VPRS modeling software for welding process, and obtained knowledge models of the low carbon steel and Al alloy GTAW dynamical process [49].

Here is a knowledge model of Al alloy GTAW process by the VPRS algorithm software.

- A3 is 1 and I is 0 and WB3 is 2 and A is 2 and I2 is 2 then WB is 6.75
- WB1 is 1 and I2 is 0 and TL3 is 0 and WT2 is 0 and A is 1 then WB is 6.75
- WB1 is 2 and TL3 is 0 and I is 0 and WB2 is 1 then WB is 6.75
- I is 2 and WT3 is 2 and WT is 0 and A1 is 1 then WB is 9.75
- A3 is 1 and I is 0 and TL is 2 and WB1 is 1 and TL2 is 2 and I2 is 2 then WB is 6.75
- A3 is 0 and WB3 is 2 and A is 1 and I2 is 2 then WB is 6.75
- WB2 is 2 and TL2 is 2 and WB3 is 1 and I2 is 0 and A3 is 1 then WB is 8.25

Fig. 15 a The Ham model schematic diagram of arc welding dynamic process. b Non-linear MIMO Ham models for Al alloy GTAW dynamic process.
3.2.3 Mixed Logical Dynamical (MLD) Modeling of Pulsed GTAW Process

In the control theory research field, 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 [52]. Our investigation shows the MLD method is highly suitable for welding dynamical process, particularly, automatic and robotic welding systems [53–56]. Our study in [53] presented a novel MLD modeling framework for robotic welding process and systems. In Fig. 17, the MLD model is then established and gives a
good prediction quality of the back bead width of pulsed GTAW process with misalignment joint during robotic welding. The study in [52] shows that the MLD framework is a good modeling method for pulsed GTAW process and robotic welding systems.

The general MLD model is described as:

\[
\begin{align*}
W_f(k) &= f_1(W_f(k-1), \ldots W_f(k-n_{W_f}), I_p(k), \ldots I_p(k-n_{I_p})) \\
L_f(k) &= f_2(L_f(k-1), \ldots L_f(k-n_{L_f}), I_p(k), \ldots I_p(k-n_{I_p})) \\
W_b(k) &= f_3(W_b(k-1), \ldots W_b(k-n_{W_b}), W_f(k), \ldots W_f(k-n_{W_f}), \\
&\quad L_f(k), \ldots L_f(k-n_{L_f}), I_p(k), \ldots I_p(k-n_{I_p}))
\end{align*}
\]

A MLD model with gap variation (WPG-MLD) is described as:

\[
\begin{align*}
W_f(k) &= 0.6328W_f(k-1) + 0.02596I_p(k) - 0.01143I_p(k-1) \\
L_f(k) &= 0.9542L_f(k-1) + 0.007477I_p(k) - 0.005348I_p(k-1) \\
W_b(k) &= 0.01666I_p(k) - 0.001824I_p(k-1) - 0.3246W_f(k) \\
&\quad + 0.09963W_f(k-1) + 0.5567L_f(k) - 0.1341L_f(k-1)
\end{align*}
\]

3.3 Intelligent Control Methods for Welding Dynamical Process

The technical approach imitating welder’s decision-making functions is to develop intelligent controller for welding process. Intelligent control strategy is mainly aiming at the objective or process with complex uncertainty. Because of especial complexity in welding dynamical process, such as strong nonlinear and
multivariable coupling process, time-variety, randomicity and involving many uncertain phenomena, it is specially suitable to adopt intelligent control strategy for it [10–12]. At present, intelligent control methods mainly include fuzzy logical, artificial neural networks, expert system and their combination control schemes [9–12, 57–61], showing as Fig. 18.

Under different welding technical conditions, such as based-on plate welding, butt welding, with filler, with gap variety and uncertainty in welding process, many intelligent control methods, Such as a self-learning fuzzy neural control, adaptive fuzzy neural control, compound intelligent controller with feed-forward compensating control methods for gap variety [61], 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 another important part in intelligentized welding systems. Although some single technical expert system has been applied in welding production, advanced autonomous expert system for control of welding dynamical process should be still investigated for mode recognition of weld workpiece, environment and seam type; autonomous programming robotic welding path and technics, intelligent control of welding process in the IWMT [11, 12].

3.3.1 Closed-Loop Control Schemes Based-on the Knowledge Model by the RS Theory

Based on the obtained knowledge rule models for weld pool dynamics of aluminum alloy GTAW by RS methods, a composited intelligent adaptive control scheme with fuzzy monitor, RS model and MS-PSD controllers was developed for Al alloy welding penetration; seam forming quality and pool dynamics during Al alloy pulsed GTAW [62], shown as in Fig. 19.

3.3.2 The Model-Free Adaptive Control of Pulsed GTAW

Arc welding is characterized as inherently multi-variable, nonlinear, time varying and having a coupling among parameters. In addition the variations in welding
conditions cause uncertainties in welding dynamics [10]. Therefore, it is very difficult to design an effective control scheme by conventional modeling and control methods. A model-free adaptive control algorithm has been developed to control the welding process [63–65], as Fig. 20, which only needs the measured input output data and no modeling requirement for controlled welding process. Thus, the developed model-free adaptive control provides a promising technology for GTAW quality control as detailed in [64]

\[
U(t) = U(t-1) + \left( R + \psi(t)^T \psi(t) \right)^{-1} \psi(t)^T \Delta Y(t+1)
\]

\[
\varphi_i(t) = \varphi_i(t-1) + \frac{\eta_i \Delta U(t-1)}{\mu_i + \| \Delta U(t-1) \|^2} \times \left( \Delta Y_i(t+1) - \Delta U(t-1)^T \varphi_i(t-1) \right)
\]
The above systematized investigation provides effective and realizable technical approaches for intelligent control of welding pool width, penetration, seam forming quality and pool dynamics during pulsed GTAW process under various conditions [11, 12]. It is a key and essential technology for the IWMT to realize intelligent control of arc welding dynamics.

3.3.3 The Adaptive Control of GTAW Process as a Nonlinear Dynamics

Based on the non-linear Ham model for arc welding dynamic process as Fig. 15 [43], The nonlinear self-tuning control systems with the Ham model of welding process have been developed for adaptive control of penetration and seam formation [43, 44]. Figure 21a is the principal of a single-input and single-output (SISO) control system, and Fig. 21b is the a double-input and double-output (DIDO) control system for the backside width and topside reinforced height of the weld seam with welding current regulation and feed-forward compensation [44].

![Nonlinear self-tuning control system with Ham model of welding dynamical process.](image)

**Fig. 21** The nonlinear self-tuning control system with Ham model of welding dynamical process. 
**a** Principal of SISO control system, **b** DIDO control system for seam formation
3.4 Intelligentized Robotic Welding Technology

Developing the intelligent welding robot (IWR) is crucial and necessary for realization of IWMT, generally, the function of IWR system involves visual sensing welding environment, recognising weld workpiece, seam type, guiding weld starting, tracking seam, instructing technics, programming paths and parameters, dominating welding pool dynamical characters, control seam forming and quality, diagnosing failures, and so on, shown as Fig. 22, i.e., the IWR is “an atom” in IWMT systems, a platform integrated by intelligented welding technologies. Based on single intelligent welding robot with collaborating positioner, an intelligented welding flexible manufacturing cell (IWFMC) could be established [13, 14]. The IWFMC could be considered as “a molecule” in the IWMT systems, which could autonomously complete a certain welding task and process [11, 12, 66].

3.4.1 The Seam Tracking During Robotic Welding by Visual Sensing

Intelligent welding robots should have some intelligent functions like welder, such as finding start welding position (SWP), adjusting the welding path and parameters according to the changing work environment [67–75]. Refs. [68, 69] developed an welding robot systems with binocular vision calculating three-dimensional (3D) coordinates of the SWP for autonomous detection and guiding of robotic welding torch motion, as Fig. 23.

The seam tracking technique and on-line quality control for the curve weld during robotic pulsed GTAW process was developed based on passive visual

![Diagram](image_url)  
**Fig. 22** The IWR technology in IWFMC
3.4.2 The 3-D Seam Tracking During Robotic Welding by Combining Arc Sensing and Visual Sensing

The guiding and tracking seam technique for three dimension (3-D) curve during robotic pulsed GTAW process was developed by the combination of arc sensing for torch height or arc length with passive visual sensing for correcting the error of seam or torch deflexion [76–80]. Figure 25 shows a robotic welding systems for 3D seam tracking by arc and visual sensing during robotic GTAW process [77].

The arc voltage signals of AC pulsed GTAW in one cycle contain base value and peak value voltage. The base value voltage is produced during piloting arc process, which can not be used to characterize the arc length. Whether the quality of welding is good largely depends on peak currents, while the corresponding peak voltage is strongly related to the arc length. Another 3D seam tracking welding example completed by robotic welding system is shown as Fig. 26 [79, 80].

Fig. 24  Welding robot system with visual sensor for monitoring welding pool and tracking seam
3.4.3 Application of Real-Time Control of Pool and Penetration During Robotic Welding by Visual and Arc Sensing

The real-time control of pool and penetration during robotic welding is very important for achieving intelligentized welding. The visual information and arc signal could be used for on-line monitoring of the welding quality [81–85]. Figure 27 shows the application experiment by the robotic welding system with arc and visual sensing for a complicated workpiece [82].

3.4.4 Development of Autonomous Welding Robot System for Special Environment

In many practical welding manufacturing sites, such as welding for ship structures and large tanks, there is a need for the autonomous moving welding in a long distance and complicated space position [11, 12]. It also requires the welding robot with adsorbent and climbing functions for all position motion and flexible pose.
changes for various joints, such as the fillet, lap, vertical, inclined welding, and so on. Hence, a primary autonomous moving welding robot system with a combination of wheels and foot for adsorbent climbing and getting across obstacle was developed [86, 87], shown as in Fig. 28. This robot system can realize some welder’s intelligent functions, such as detecting and recognizing weld surroundings by visual sensing technology, identifying the initial position of weld seam, autonomously guiding weld torch to the weld starting and tracking the seam, real-time control of arc weld pool dynamics. In order to ensure the obstacle-crossing and the welding process are conducted in the same time, The programming tracks of robot obstacle-crossing motion has been studied in [88].

3.4.5 The Complicated Modeling and Control Methodology for the Intelligentized Welding Manufacturing Systems (IWMS)

The intelligentized welding manufacturing systems (IWMS) is a highly complicated systems, which contains not only the complex welding equipments, such as welding robot, welding machine, fixtures and chucking appliance and so on; a large mixed information variables, such as continuous and discrete variables, logical rules and operating constraints; and various sensors, information processing units, computing
and intelligent units, and so on [10–12]. The IWMS can be classified as a typical hybrid system in advanced control theory [52]. One can see that the modeling and dominating of the IWMS is extremely difficult.

1. A MLD Model for Robotic Welding Systems

Aiming at the hybrid characteristics in the IWMS, mixed with the continuous and discrete variables, logical rules and operating constraints, Ref. [54] presented the so-called mixed logical mixed logical dynamical (MLD) models for the robotic welding systems as following:

\[
\begin{bmatrix}
    x_r(t+1) \\
    x_b(t+1)
\end{bmatrix} = \begin{bmatrix}
    A_{rr} & A_{rb} \\
    A_{br} & A_{bb}
\end{bmatrix}\begin{bmatrix}
    x_r(t) \\
    x_b(t)
\end{bmatrix} + \begin{bmatrix}
    B_{1rr} & B_{1rb} \\
    B_{1br} & B_{1bb}
\end{bmatrix}\begin{bmatrix}
    u_r(t) \\
    u_b(t)
\end{bmatrix} + \begin{bmatrix}
    B_{2rb}
\end{bmatrix}d(t)
\]

\[
= \begin{bmatrix}
    B_{3rr} \\
    B_{3rb}
\end{bmatrix}z(t) + \begin{bmatrix}
    B_{5r}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    Y_r(t) \\
    y_b(t)
\end{bmatrix} = \begin{bmatrix}
    C_{rr} & C_{rb} \\
    C_{br} & C_{bb}
\end{bmatrix}\begin{bmatrix}
    x_r(t) \\
    x_b(t)
\end{bmatrix} + \begin{bmatrix}
    D_{1rr} & D_{1rb} \\
    D_{1br} & D_{1bb}
\end{bmatrix}\begin{bmatrix}
    u_r(t) \\
    u_b(t)
\end{bmatrix} + \begin{bmatrix}
    D_{2rb}
\end{bmatrix}d(t)
\]

\[
= \begin{bmatrix}
    D_{3rr} \\
    D_{3br}
\end{bmatrix}z(t) + \begin{bmatrix}
    D_{5r}
\end{bmatrix}
\]

\[
E_2d(t) + E_3z(t) \leq E_1\begin{bmatrix}
    u_r(t) \\
    u_b(t)
\end{bmatrix} + E_4\begin{bmatrix}
    x_r(t) \\
    x_b(t)
\end{bmatrix} + E_5
\]

2. A Petri Net Model for Three-robot Welding Systems

Aiming at the information concurrency in the IWMS, e.g., synchronous conflicts between information flow and materials flow, Refs. [89–91] presented some improved Petri net models for multi-robot welding system and welding production line, the Petri net modeling method is very suitable for discrete-event property in the IWMS. Here Fig. 29 shows an improved PN model with sensing information for three robotic welding systems.

3. A MAS Model for Multi-robot Welding Flexible Production Line Systems

Considering to the intelligent processing functions in multi-robot welding flexible production line systems with distributed multi-sensors, information exchange and communications, Refs. [92–96] presented some Multi-Agents (MAS) models for complicated multi-robot welding system and welding production line, the MAS theory and technology has become an important approach for modeling and control of complex manufacturing systems. Here Fig. 30 shows an improved MAS models with sensing information for complicated multi-robot welding systems or welding production line.
Fig. 29 An improved PN modeling of multi-robot welding systems. a Schematic diagram of 3-robot welding systems, b the PN model of 3-robot welding systems
4. A multi-agents method for IWMS
The MAS modeling and control method, are highly suitable for the IWMS, we developed an improved MAS model for the IWMS in this paper, as Fig. 31.

3.5 On Intelligentized Welding Manufacturing Engineering

Based on the IWMT related to scientific and technical researching contents, a concept on intelligentized welding manufacturing engineering (IWME) is introduced for a systematized research and application engineering of the IWMT/S. Figure 32 shows for a simple subject compositions of the pentabasic IWMT/S schematic diagram for an intelligentized welding manufacturing workshop (IWMW), which briefly reveals the main scientific and technical elements of the IWME [97–100]. And Fig. 33 is an example application of the IWME for the IWMW of the oceanic drill platform.
Multi-agent Administration for Intelligentized Welding Manufacturing Systems

Fig. 31 The MAS model for IWMS. Abbreviations: IWMS intelligentized welding manufacturing systems; WP welding process; R robot; P production; QT quality test; W welding; AD administration; S system; U unit

Fig. 32 The pentabasic IWMT/S schematic diagram for the IWMW. IT informatization technology; IS intelligent System; DT digitization technology; VS virtuality system; NT networking technology; DS distributed systems; RT robot technology; FS flexible systems; WT welding technology; MS manufacturing systems
In this paper, we have presented some concepts on intelligentized welding manufacturing (IWM), and the framework and constitution of technologies and systems for the IWM, such as the intelligentized welding manufacturing technology/systems (IWMT/S), intelligentized robotic welding technology/systems (IRWT/S) and intelligentized welding manufacturing engineering (IWME). The author hopes that it is instructive to investigate the IWM as a systematization of intending research framework and constitution on the IWMT/S. This paper has also shown some new evolutions of research results on the IWMT/S in the IRWTL at SJTU.

At present, there is an evident trend that artificial intelligent technology is widely used into almost manufacturing and engineering processes. The motivation of introducing the concepts, IWMT/S, IRWT/S, and IWME, research framework and constitution of intelligentized welding manufacturing in this paper, is to promote systematization research for forming an organic combination of modern welding manufacturing and artificial intelligent technology.

Fig. 33 The IWME schematic diagram for the IWMW of oceanic drill platform

4 Conclusion
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