Metaverses-Based Parallel Oil Fields in CPSS: A Framework and Methodology

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***Abstract*—Aiming to provide a novel paradigm of oil fields, metaverses-based parallel oil fields are proposed in this article. Compared with the existing smart/intelligent oil fields in cyber–physical systems (CPS), parallel oil fields can take human factors into full consideration and expand the operation space to cyber–physical–social systems (CPSS), which can be regarded as the abstract and scientific explanation of metaverses. In the proposed parallel oil fields, there are three kinds of workers (human workers, digital workers, and robotic workers) coordinating to construct a more reliable and intelligent oil field. Furthermore, the framework and methodology of parallel oil fields are illustrated by parallel systems and the artificial systems, computational experiments, and parallel executions (ACP) approach. Based on the proposed framework, parallel oil fields are capable of generating a more trustworthy artificial system and guaranteeing the realization of the 6S (safety, security, sustainability, sensitivity, service, and smartness) goal. Finally, based on dynamometer cards, fault diagnosis of sucker rod pumping systems (SRPS) is investigated in parallel oil fields.**

***Index Terms*—Artificial systems, computational experiments, and parallel executions (ACP) approach, Cyber–physical–social systems (CPSS), digital workers, fault diagnosis, metaverses-based parallel oil fields, parallel systems.**

I. INTRODUCTION

WITH the rapid development of technology and computer science, Industry 4.0 is officially proposed in 2013, and its core features can be: cyber–physical systems (CPS) [1], [2], Internet of Things (IoT) [3], [4], digital twins [5], [6], and so on. Based on Industry 4.0, vertical and horizontal manufacturing integration and product connectivity will help companies achieve higher industrial performance [7]. However, human factors are not fully considered in CPS, which are also an essential part of actual industries. By introducing cyber–physical–social systems (CPSS) [8] to industries, Industry 5.0, proposed by Wang et al. [9], can fully consider human factors and make up for Industry 4.0's shortcomings, thus ushering in a new industrial era (as shown in Fig. 1). It is believed that Industry 5.0 will bring more technological changes and provide more opportunities.

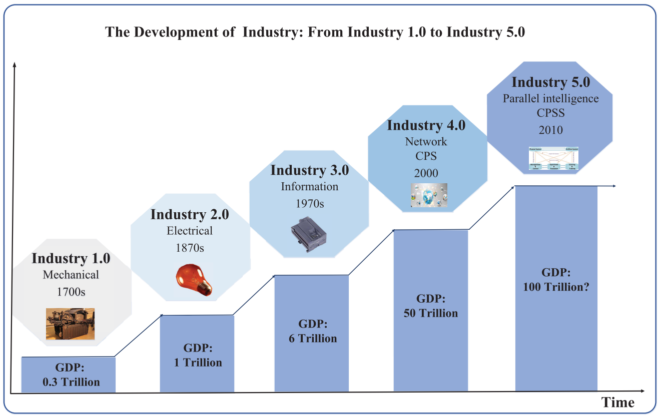

Fig. 1. Development of industry.

Inside industries, oil is an indispensable element and is crucial to almost everyone's daily life. Given the fact that oil is a nonrenewable energy resource, more and more researchers begin to focus on how to increase oil production. Also, along with the development of information technology, the operation and management in oil fields are facing a new revolution [10]. Nowadays, the phrase "smart/intelligent oil fields [11]" or "oil and gas 4.0 [12]" denote the undergoing revolution in oil fields. Nonetheless, there is ambiguity not only on their incremental benefits but also on the criteria and conditions of applicability technical and economicwise [13]. What is worse, on the basis of Industry 4.0, the operation space of smart/intelligent oil fields is CPS [14], which makes it less feasible for physical oil fields. It is this situation that motivates us to explore a new paradigm shift in oil fields.

Fortunately, parallel systems, proposed by Wang in 2004 [15], provide a solution for these problems. They are initially put forward to deal with complex systems. The core element in parallel systems is the Artificial systems,

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Computational experiments, and Parallel executions (ACP) approach [16], which is a trilogy: artificial systems (A), computational experiments (C), and parallel executions (P) [17]. After years of research and accumulation, parallel systems have been successfully applied to plenty of fields, such as parallel vision [18], parallel learning [19], parallel transportation [20], parallel control [21], and so on [22], [23], [24], [25]. These successful applications further verify the powerful performance of parallel systems, which indicates it will be feasible for oil fields. It is also worth noting that metaverses [26], a hot topic since 2020, is stepping from science fiction to an upcoming reality [27]. However, just like smart/intelligent oil fields, there is not a specific definition for metaverses, and different people can hold different views on this issue. From the engineering perspective, the metaverses have the typical characteristics of CPSS [28], and CPSS is the abstract and scientific name for metaverses [29]. Therefore, based on parallel systems and CPSS, metaverses-based parallel oil fields are proposed in this article to guarantee oil fields' better performance. The main contributions of this article are listed as follows.

1) In contrast to smart/intelligent oil fields, metaverses-based parallel oil fields are proposed in this article to take human factors into full consideration.
2) By integrating human workers, digital workers, and robotic workers into oil fields, a new framework for parallel oil fields is established.
3) With the ACP approach, the operation process of parallel oil fields is constructed, which can enable human–machine interactions to work more effectively.
4) Based on dynamometer cards, fault diagnosis of sucker rod pumping systems (SRPS) in metaverses-based parallel oil fields is investigated to provide a novel diagnostic paradigm for oil fields.

The remainder of this article is organized as follows. Section II introduces the development of smart/intelligent oil fields. Then, Section III describes the framework and operation process of metaverses-based parallel oil fields. Afterward, supporting technologies in parallel oil fields are listed in Section IV. Next, based on dynamometer cards, fault diagnosis of SRPS in parallel oil fields is investigated in Section V. Finally, Section VI draws the conclusion of this article.

II. SMART/INTELLIGENT OIL FIELDS

The rapid development of digital technology and IoT accelerates technological revolutions in oil fields. Following the footsteps of digital oil fields [30], smart/intelligent oil fields are proposed to bring about new scientific advances. There is no doubt that they have achieved the purpose of increasing storage and efficiency, which can improve oil recovery and economic benefits [31]. Additionally, the evolution of oil fields is shown in Fig. 2.

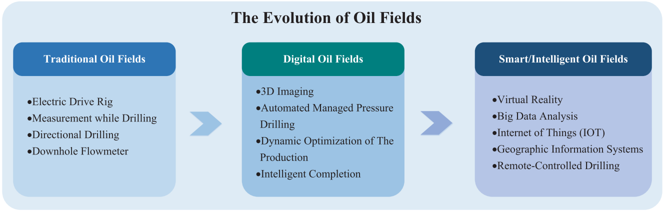

Fig. 2. Evolution of oil fields.

To achieve these assumed performances of smart/intelligent oil fields, many advanced technologies are integrated into their systematic designs. Due to page limitations, some supporting technologies are briefly listed in the following.

1) CPS [32], [33].
2) IoT [34], [35].
3) Big data analysis [36], [37].
4) Digital twins [38], [39].
5) Blockchain technology [40], [41].
6) Wireless sensors network [42], [43].
7) Other significant technologies [44], [45], [46], [47], [48], [49].

Although smart/intelligent oil fields have obtained fruitful advances, it is worth noting that they are studied in CPS. In other words, smart/intelligent oil fields only consider the interaction between physical worlds and cyber worlds and lack consideration for social worlds, which also play an important role in oil fields. Therefore, the existing research status indicates that a new organization structure of oil fields is of great urgency. Based on CPSS and parallel systems, metaverses-based parallel oil fields are proposed in this article to provide a novel paradigm shift and bring new development opportunities to oil fields.

III. METAVERSES-BASED PARALLEL OIL FIELDS IN CPSS

Since 2020, metaverse becomes a popular topic, and its main characteristic is interactions between physical worlds and virtual worlds. As for the abstract and scientific name for metaverses, CPSS can serve as a solid tool, which emphasizes in-depth interaction among physical worlds, cyber worlds, and social worlds [50]. Moreover, since firstly coined in 2010 [8], CPSS has applied into various domains [51], [52], [53]. Based on CPSS and parallel systems, metaverses-based parallel oil fields in CPSS are proposed in this article. The detailed descriptions of the framework and operation processes are given in the following sections.

A. Framework of Metaverses-Based Parallel Oil Fields

On the basis of CPSS, there are three kinds of workers in metaverses-based parallel oil fields: 1) human workers; 2) digital workers; and 3) robotic workers. The detailed relationships among these workers are shown in Fig. 3, in which they will cooperate together to accomplish difficult tasks.

In parallel oil fields, human workers are divided into two kinds: one represents leaders that have the highest authority to deliver orders to other workers; the other works in physical oil fields to react to special situations where digital workers and robotic workers cannot handle. When it comes to digital workers, they can serve as intermediaries between human workers and robotic workers. Upon receiving the delivered orders, digital workers will figure out an optimal policy to finish these orders through related supporting technologies.

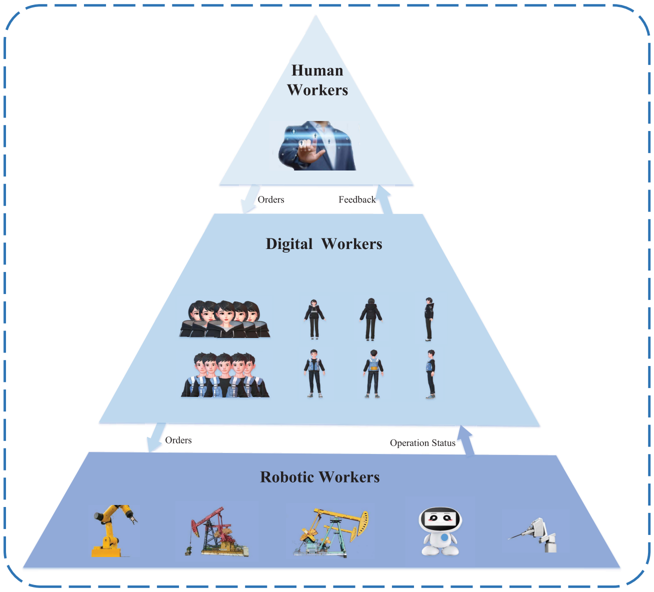

Fig. 3. Different workers in parallel oil fields.

After the optimal policy is obtained, it will be sent to robotic workers, where the policy is carried out in physical worlds. Afterward, operation results in robotic workers are transmitted to digital workers, who will evaluate whether orders are fully accomplished. Finally, digital workers will report evaluations results to human workers. The more this process is repeated, the more stable and advanced oil field will be obtained.

Remark 1: Many commentators are forecasting a terminal decline in the production of conventional oil [54]. What is worse, due to the continuous decrease in production rates of SRPS, the number of installations of SRPS in extreme environments is increasing [55]. By introducing digital workers to parallel oil fields, the number of human workers in tough areas is dramatically reduced, thus, lessening economic inputs and ensuring the safety of human workers.

In the following, the overall framework of metaverses-based parallel oil fields is shown in Fig. 4. In the framework of parallel oil fields, there are three layers: 1) command layer; 2) digital layer; and 3) executive layer. Each layer has different functions, and they can cooperate to present a more safe and more reliable oil field. Different tasks/orders, such as improvement of economic returns, and business continuity planning, are set by some human workers in the command layer, where the social factor is considered, and then delivered to the digital layer. When these tasks/orders are completely finished, the digital layer will provide feedback to this layer.

As for the digital layer in cyberspace, its core element is digital workers. This layer mainly includes two sections: 1) the communication section and 2) the field section. The communication section aims to assist digital workers in understanding the meaning of tasks/orders, making orders and feedback more understandable. The key algorithms adopted in the communication section are natural language processing foundation models [56], [57] and image foundation models [58], [59]. With these embedded models, digital workers are more capable of understanding and responding to those issued tasks/orders. After understanding what the command layer delivers, the field section will come up with an optimal policy to complete these tasks/orders. In parallel oil fields, EuArtisan, the field foundation model proposed in [60], is utilized to promote better performance. For EuArtisan, the most noteworthy element is the introduction of scenarios engineering (SE) [61], whose basic goal is to establish trustworthy artificial intelligence (AI) techniques. In this part, SE-based modeling will analytically build more reliable and practicable oil models, and generate a more useful dataset. After developing the optimal policy for specific tasks/orders, it will be delivered to the executive layer, where actions are carried out in physical oil fields.

After executing the issued optimal policy, the operation status of robotic workers in physical oil fields will be transmitted to the digital layer, in which whether the delivered tasks are completed is evaluated. Finally, the digital layer will report the executive situation of delivered orders to the command layer, and final decisions will be made in the highest layer.

B. Operation Process of Metaverses-Based Parallel Oil Fields

In this section, the operation process of parallel oil fields is provided. Based on the ACP approach, parallel oil fields will achieve the aforementioned powerful performance. There are three foundation stones in the ACP approach: 1) artificial systems [62]; 2) computational experiments [63]; and 3) parallel executions [64]. Under the ACP methodology, the operation process of metaverses-based parallel oil fields is illustrated in Fig. 5. And a thorough and comprehensive description of the operation process is given as follows.

1) *Artificial Systems:* In parallel oil fields, the primary issue is to construct artificial oil fields, which can present a variety of oil fields' working conditions. Different from traditional model methods in oil fields, such as digital twin [65], artificial systems in parallel systems aim to build one or more systems that include different situations and provide more useful instructions for managements of physical oil fields. That is, depending on plenty of needs, one physical oil field can interact with multiple virtual artificial oil fields [66].
2) *Computational Experiments:* After the construction of artificial oil fields, the next important thing is to observe how different policies will influence physical oil fields. The basic idea in computational experiments is to proactively generate diverse behaviors of experimental systems in a bottom-up fashion via interactions of artificial objects [67]. Among computational experiments, there are three key patterns: a) management & control; b) experiments & evaluation; and c) learning & training. The main features of each pattern are listed in the following.
    a) *Management and Control:* In this part, artificial oil fields will try to estimate physical oil fields as accurately as possible to provide references for management and control in physical oil fields. Furthermore, biases between physical oil fields and artificial oil fields are applied to optimize parameters in artificial oil fields, thus, generating more accurate estimations and better control policies.

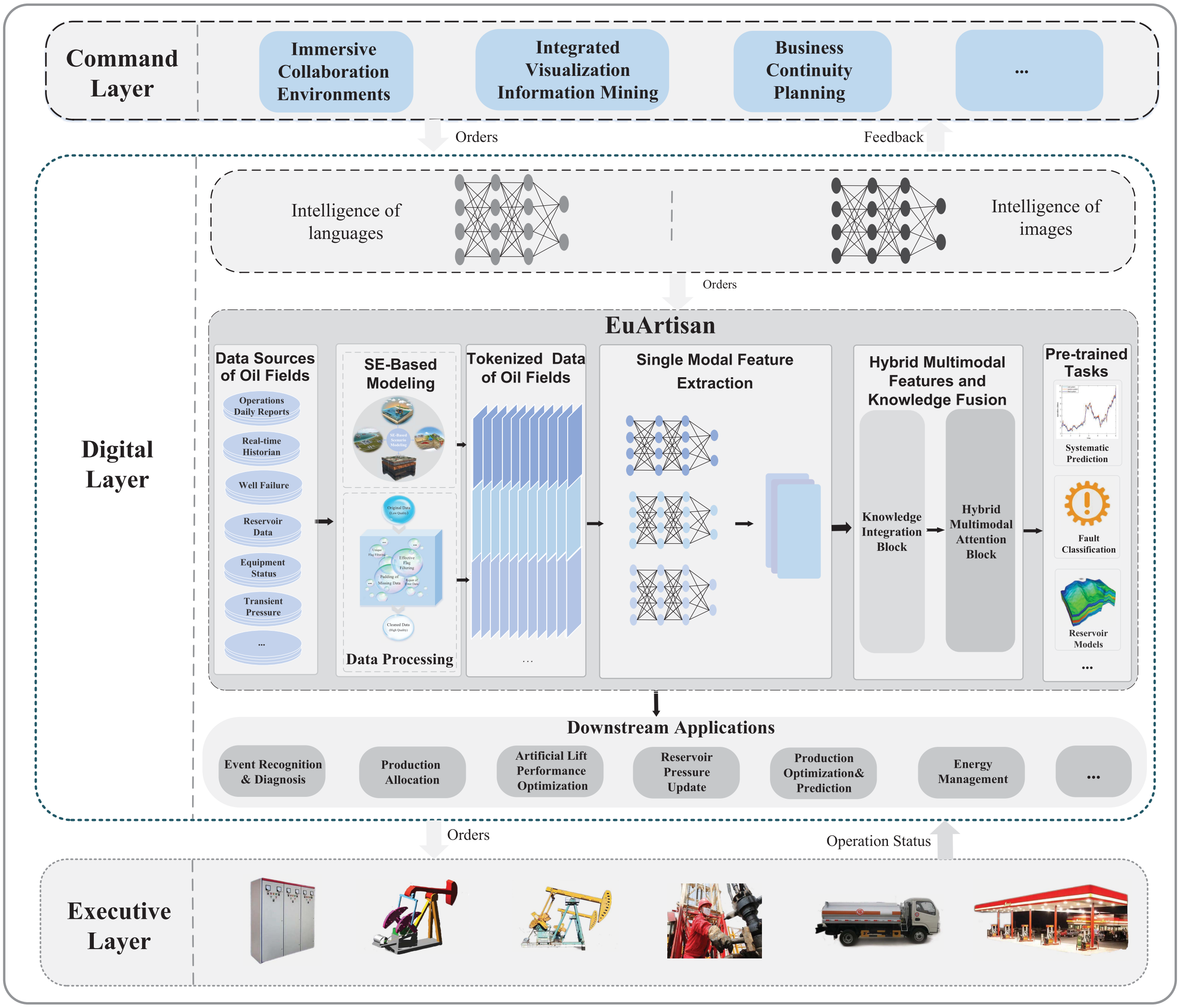

Fig. 4. Framework of metaverses-based parallel oil fields.

b) *Experiments and Evaluation:* This process is mainly for generating and conducting computational experiments, and for testing and evaluating various system scenarios and solutions [66]. With this process, behaviors and reactions of different policies are tested and evaluated, which can provide guidance for management and control of physical oil fields.

c) *Learning and Training:* In this pattern, artificial oil fields can be viewed as training centers to help human workers develop professional skills. Then, with connections between physical and artificial oil fields, human workers that manage and control physical oil fields can quickly respond to plenty of situations and take proper measures to reduce economic and human losses.

3) *Parallel Executions:* Physical and artificial oil fields will each operate in their respective ways in this section. Based on the computational experiments, the operation status of physical oil fields will be monitored by transmitting operation data to this section. If there exist abnormal situations in physical oil fields, guidelines to bring them back to normal production will be timely provided by results in computational experiments.

With the integration of the ACP approach and supporting technologies, it is noted that parallel oil fields can realize these powerful performance and generate more efficient oil fields. Moreover, with the training of human workers, more specialized workers will help construct a more safe oil field. Finally, the 6S (safety, security, sustainability, sensitivity, service, and smartness) goal [68] will be realized to construct more reliable and trustworthy oil fields.

IV. SUPPORTING TECHNOLOGIES

To support parallel oil fields, certain technologies are necessary to help achieve the desired performances. As shown in Fig. 6, some of the adopted technologies can be:

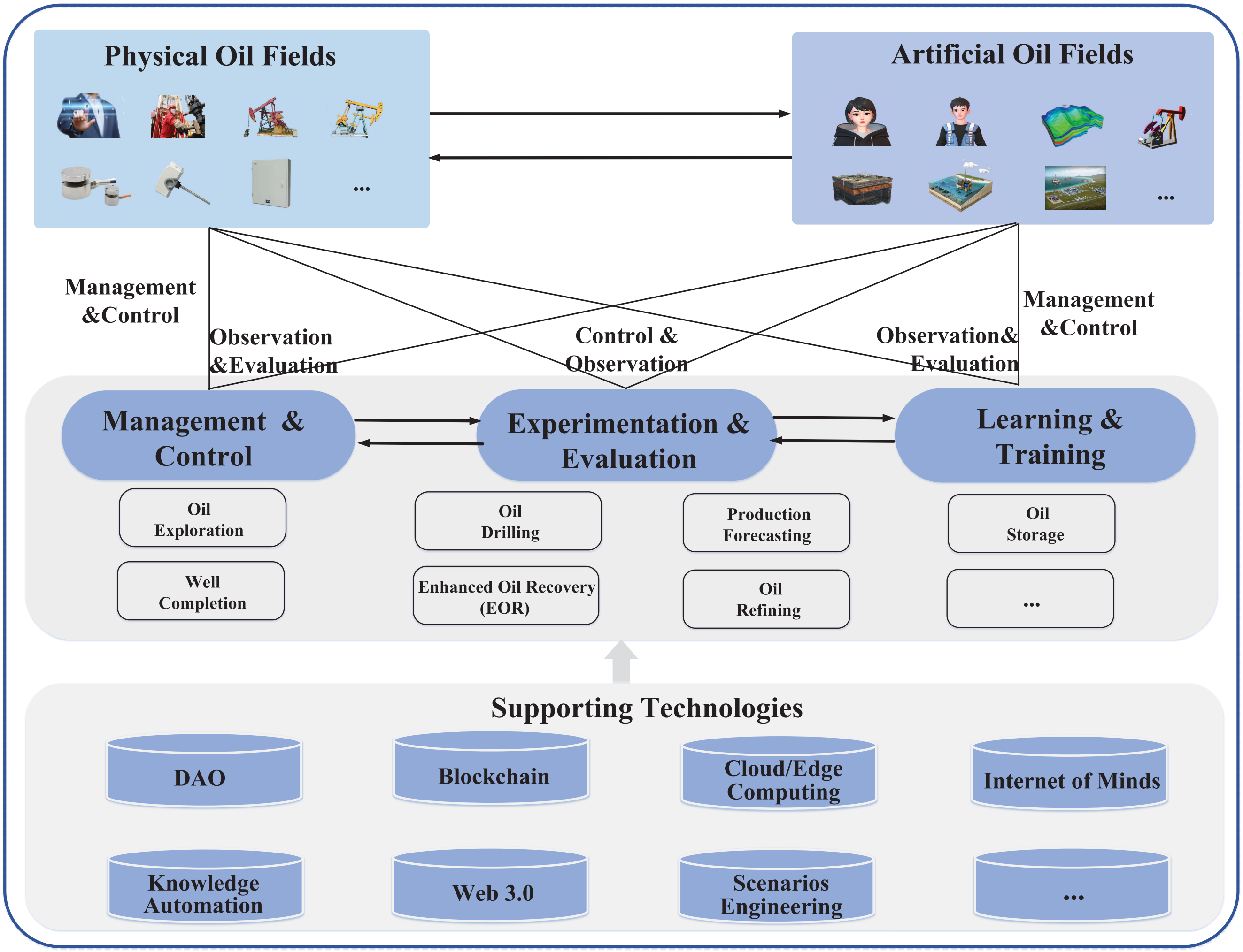

Fig. 5. Operation process of metaverses-based parallel oil fields.

Fig. 6. Supporting technologies in parallel oil fields.

blockchain, cloud/edge computing, Web 3.0, SE, decentralized autonomous organization (DAO), smart contract, knowledge automation, and so on. However, due to page limitations, part of the supporting technologies are listed in the following.

A. Blockchain

Originating from Bitcoin [69], blockchain technology is able to offer a high level of security and prevent data from altering by integrating distributed data storage, timestamp, and consensus algorithm [70]. Moreover, it is a novel and fundamental technical framework and has imposed significant effects on many fields, such as cryptocurrency [71], enterprise management [72], smart grid [73], smart manufacturing [74], multimicrogrid systems [75], and so on [76], [77]. Aiming to provide guidance and reference for future study, the framework of a complete blockchain system is given in [78]. According to [79], blockchain is used to support the running of smart contract, which are computer protocols intended to digitally facilitate, verify, or enforce the negotiation or performance of a contract [80]. In the area of parallel oil fields, blockchain can be used to guarantee the safety of vast amounts of data.

B. DAO

With the emergence of blockchain, DAO is gaining more and more attention. As for its origin, DAO can be traced back to swarm intelligence [81], [82], [83] and cyber movement

Fig. 7. SRPS in physical oil fields.

organizations [84]. In [85], DAO is defined as: a blockchain-powered organization that can run on its own without any central authority or management hierarchy. Further in [86], the definition of DAO is: a human–machine hybrid governed self-organization by smart contracts running on blockchain without centralized hierarchy. Moreover, in [87], the concept of DAO is: a blockchain-based system that enables people to coordinate and govern themselves, and whose governance is decentralized. Although there is no consensus on how to define a DAO [88], they all emphasize the organizations without central authority or management, which allows individuals to collaborate in a nontraditional work environment. The introduction of DAO is anticipated to dramatically reduce the costs associated with communication and management for organizations. In the proposed parallel oil fields, DAO can provide a way for workers to complete tasks independently.

C. SE

The continued development of AI has led to the generation of many innovative methods that are based on feature engineering. Although these algorithms can be very accurate, they tend to be less reliable and more difficult to interpret. In [61], scenarios engineering for building trustworthy AI techniques is presented. Six key dimensions, intelligence & index (I&I), calibration & certification (C&C), and verification & validation (V&V), are given to obtain a more robust and reliable AI. In brief, I&I provides the scenarios-based intelligent ecology for AI; C&C ensures parameters of the constructed system are at reasonable levels, and V&V can effectively evaluate the performance and functions of AI. With the embedded SE modeling, more credible artificial oil fields are constructed in metaverses-based parallel oil fields.

D. Cloud Computing

Just like real clouds that are the collection of water molecules, the term "cloud" in cloud computing is the collection of networks [89]. Many believe that it will reshape the IT industry as a revolution [90]. It does have revolutionized several industries for several years [91]. Although there are so many definitions [92], some authors decided to bring them together [93]. The one thing they all have is the focus on the network. With this network, cloud computing offers cloud users elastic resources that can be acquired and released on demand [94]. In the design of parallel oil fields, cloud computing can be used for computational experiments to achieve the goal of "local simple, remote complex [95]."

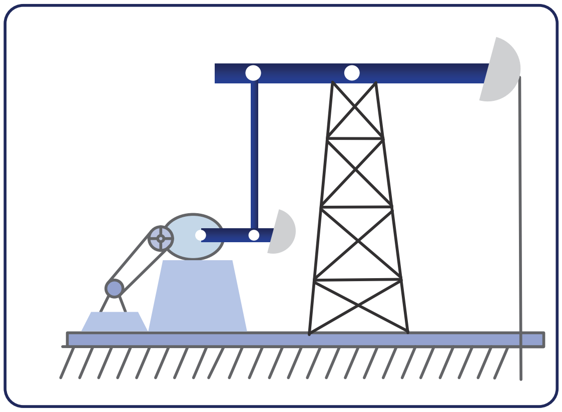

Fig. 8. Four-link structure of SRPS.

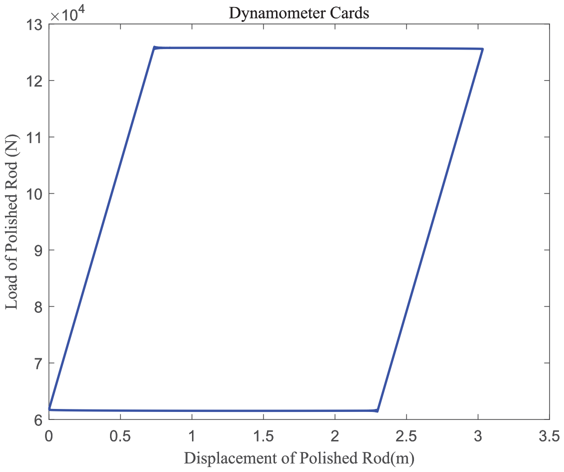

Fig. 9. DC under normal working conditions.

V. FAULT DIAGNOSIS FOR SUCKER ROD PUMPING SYSTEMS IN PARALLEL OIL FIELDS

In oil fields, how to drill oil to the ground is one of the most crucial issues. To achieve this goal, many technologies have been proposed. Among these technologies, the most popular one is artificial lift technology [96]. One of the mostly adopted artificial lift technology is SRPS, which are viewed as a well-established technology in the oil and gas industry [97]. Fig. 7 illustrates different structures of SRPS in various physical oil fields.

As shown in Fig. 8, among these structures, the most popular one is the four-link structure. Nevertheless, during the operation of SRPS, faults are an inevitable subject. Whenever the equipment operates in faulty states, these situations may have severe impacts on productive efficiency and safety [98], thus doing great damage to oil fields. In order to obtain a more thorough comprehension, fault diagnosis in SRPS receives greater attention. After years of research, many theories have

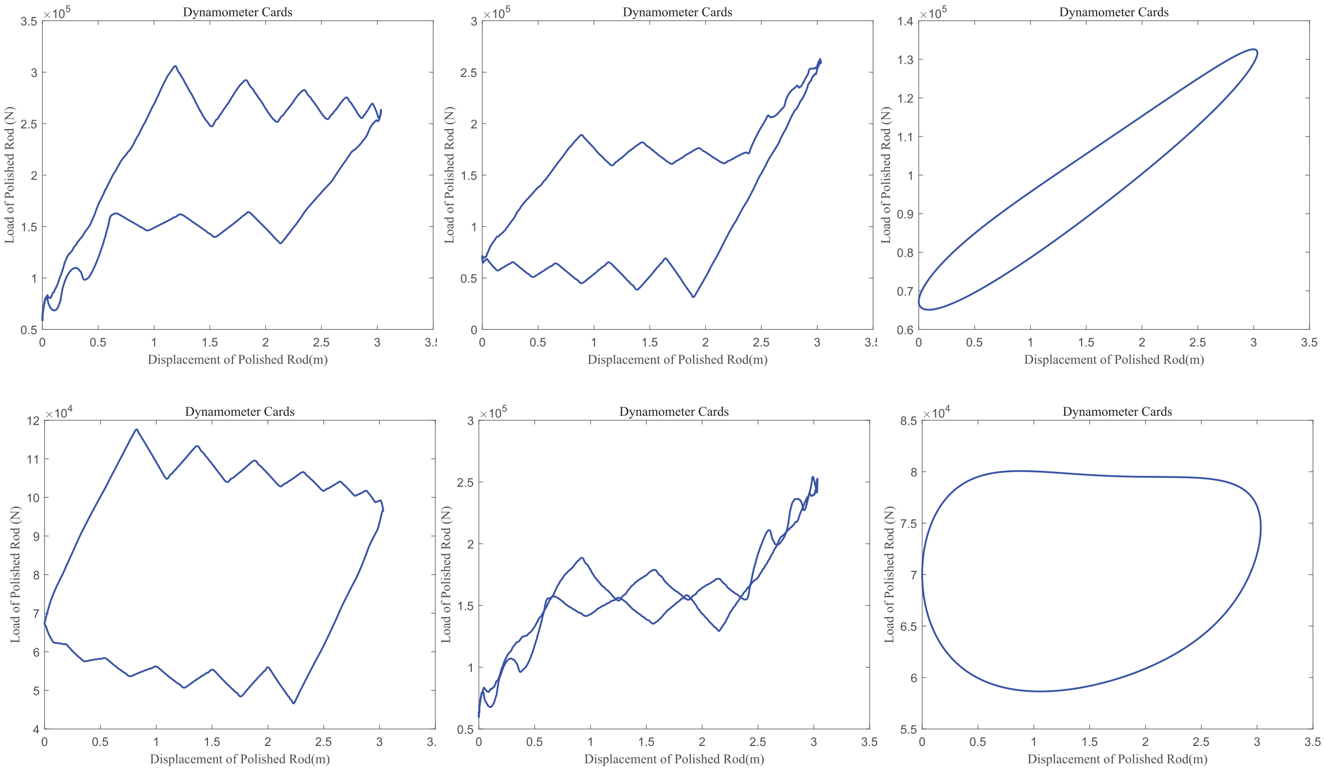

Fig. 10. DCs under abnormal working conditions.

been proposed to accurately diagnose operation status of SRPS and promote the efficiency of oil fields.

In fault diagnosis, dynamometer cards (DCs) are one of the most effective ways to evaluate whether faults exist in the operating SRPS. Theoretically speaking, DC is a closed curve that represents loads of polished rod versus displacements of SRPS in a single operation cycle [99]. The origin of this method can be traced back to 1936 [100]. For DC, if faults do not exist in the operation process, the ideal shape of DC can be a parallelogram, as shown in Fig. 9. Once faults occur, the shape of DC can change to various forms. Among these faults, some of the most common ones can be: standing valve leakage, traveling valve leakage, gas influence, insufficient liquid supply, plunger moving out of the barrel, tubing leakage, pump bumping, pump sticking, rod parting, and abnormal properties of well fluid [101]. Part of DCs with abnormal working conditions are listed in Fig. 10.

Notwithstanding, as mentioned in Section II, the existing smart/intelligent oil fields lack consideration for human factors, which also reflects in fault diagnosis of SRPS. Moreover, most existing diagnostic algorithms focus on how to improve diagnostic accuracy by integrating various intelligent algorithms [102], [103], [104], [105]. Consequently, these studies fail to consider the impacts of data sources on diagnostic accuracy, and only few researchers [99], [106] pay attention to this issue. Given this situation, a novel diagnostic paradigm is proposed through parallel systems. Some of our preliminary works can be found in [107] and [108]. Based on metaverses-based parallel oil fields, a new perspective of fault diagnosis in SRPS can be achieved by the joint efforts of human workers, digital workers, and robotic workers. Through parallel systems, artificial SRPSs can offer more dependable data for fault diagnosis. With the integration of human factors, more professional workers will be trained through learning & training in the ACP approach. When faced with some difficult and tricky situations, these well-trained human workers will take the most effective measures to greatly reduce economic losses. In addition, if the occurred faults will potentially harm human workers, they can devise the most suitable strategy to ensure their safety. The operation status of SRPS will also be monitored by digital workers, who are capable of working around the clock and handling difficult cases. Moreover, digital workers can significantly lighten the load of human workers and create a more suitable working environment to human workers. Consequently, the proposed parallel diagnostic paradigm can construct a more reliable and solid oil field, and lead to a remarkable boost in oil production.

VI. CONCLUSION

In order to provide a new operation way for oil fields, metaverses-based parallel oil fields are put forward in this article. Different from smart/intelligent oil fields in CPS, the operation space of parallel oil fields is extended to CPSS, where the proposed oil fields can take human factors into full consideration and systematically design more solid systems. With the integration of human workers, digital workers, and robotic workers, an innovative operation mode is provided in parallel oil fields. Based on the ACP approach and parallel systems, the framework and methodology of parallel oil fields were given to provide guidance for better implementation. Finally, DCs-based fault diagnosis of SRPS in metaverses-based parallel oil fields was studied to promote oil production. In the future, the automation of oil fields will be deeply investigated through the proposed parallel oil fields.

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