An Agent-Based Hybrid Intelligent System for Petroleum Reservoir Characterisation

Chunsheng Li[1], Zili Zhang[2, 3] and Fuhua Shang[1]
[1]College of Computer and IT, Daqing Petroleum Institute, Heilongjiang, 163318, China
csli@pislab.com, fhshang@pislab.com
[2] Faculty of Computer and Information Science, Southwest China University, Chongqing 400715, China
[3]School of Information Technology, Deakin University, Geelong, VIC 3217, Australia
zzhang@deakin.edu.au

Abstract

Petroleum reservoir characterisation is a new practical technology for synthetically studying and evaluating petroleum reservoirs. Since the complexity of the underground geology, a single intelligent technique can not solve the complicated and elaborate geologic problems. It is necessary that those geologic problems are synthetically studied by combining multiple intelligent techniques. We discuss an agent-based hybrid intelligent system for solving petroleum reservoir characterisation. The system starts with the digitisation of well logs parameter graphs based on an expert system. The identification of lithology and the prediction of porosity and permeability can be conducted by using hybrid intelligent techniques. Four intelligent technique agents (the complicated lithology identification with parthenogenetic algorithm, the porosity prediction with neural network, the permeability estimation with fuzzy neural network, and the well logs curve-digitizing with expert system) have been integrated. The prototype of the petroleum reservoir characterisation system has been implemented by using C language and Socket technique. The legacy resources can be used in the system by means of middleware agents. The robustness of the system is facilitated through the use of the redundant middle agents with ring-based architectural model.

1 Introduction

Petroleum reservoir characterisation is a new practical technology for synthetically studying and evaluating petroleum reservoirs. Petroleum reservoir characterisation includes many research subjects, e.g., prediction and calculation of parameters of reservoir properties, distribution of pressure, lithofacies identification. However, lithology, permeability, and porosity are the three most important parameters. Since the complexity of the underground geology, a single intelligent technique is not enough to solve the complicated and elaborate geologic problems. It is necessary that those geologic problems are synthetically studied by combining multiple intelligent techniques [1].

The petroleum reservoir characterisation system starts with the digitisation of well logs parameter graphs based on an expert system. The identification of lithology and the prediction of porosity and permeability can be conducted by using hybrid intelligent techniques. The system has integrated four intelligent technique agents (the complicated lithology identification with parthenogenetic algorithm, the porosity prediction with neural network, the permeability estimation with fuzzy neural network, and the well logs curve-digitizing with expert system). We develop the petroleum reservoir characterisation system with the process stages of the methodology for constructing agent-based hybrid intelligent systems (MAHIS for short) [2].

Under the support of the platform for agent-based hybrid intelligent systems (PAHIS for short) [2], the prototype of the petroleum reservoir characterisation system has been implemented by using C language and Socket technique. The legacy resources can be used in the system by means of middleware agents. The robustness of the system is facilitated through the use of the redundant middle agents with ring-based architectural model.

The remaining sections of this paper are organized as follows: Section 2 introduces MAHIS. Section 3 presents the system development. Section 4 describes the system implementation. Section 5 concludes the paper.

2 Outline of MAHIS methodology

MAHIS attempts to direct users to develop their agent-based hybrid intelligent systems (HIS) from the descriptions of the problems which are needed to be solved to the output of the specifications which can be implemented directly. It consists of eight models: *Hybrid*

Strategy Identification Model, *Organization Model*, *Task Model*, *Agent Model*, *Expertise Model*, *Coordination Model*, *Reorganization Model*, and *Design Model*.

The models of MAHIS are classified into three levels: conceptualization level, analysis level, and design level in accordance with the three process stages of MAHIS. The conceptualization level includes the *Hybrid Strategy Identification Model* and the description of hybrid problem requirements. During this phase, an elicitation task to obtain a preliminary description of the hybrid problem is carried out. Based on the problem description, the hybrid strategy model adopted by the HIS is identified. The purpose to identify the hybrid strategy is to help other models to decide the architectural model of the HIS because the hybrid strategy adopted by a hybrid intelligent system decides the organizational structure and coordination mechanism of the system. The analysis level includes the *Organization Model*, *Task Model*, *Agent Model*, *Reorganization Model*, *Expertise Model*, and *Coordination Model*. These models can be classified into two sublevels: context and concept. The context sublevel includes the *Organization Model*, *Task Model*, and *Agent Model*, which attempt to clarify the tasks, agents, organizational context, and environment. The concept sublevel includes the *Reorganization Model*, *Expertise Model*, and *Coordination Model*, which issue the conceptual descriptions of the knowledge applied in a task, the interactions between agents, and the hierarchical structure and the primitive members in each level. The design level only includes the design model which consists of four steps: architecture design, agent communication language (ACL) design, platform design, and application design.

The hybrid problem to be solved is represented in the *Hybrid Problem Requirements*. The information in the *Hybrid Problem Requirements* can be used to develop the *Hybrid Strategy Identification Model*, *Organization Model*, *Task Model*, and *Agent Model*. The *Organization Model* supports the analysis of the major features of an organization in order to describe the organization into which the HIS is going to be introduced and the social organization of the agent society. The *Task Model* analyses the global task layout, its inputs and outputs, preconditions and performance criteria, as well as needed resources and competences. The *Agent Model* describes the agent characteristics: groups and hierarchy. The purpose of the *Expertise Model* is to explicate in detail the types and structures of the knowledge used in performing a task. The *Coordination Model* describes the conversations between agents: their interactions, protocols and required capabilities. The *Reorganization Model* is the key model to support platform-based HIS. It consists of category role, group roles, virtual organization role, and dynamics rules. This model describes the hierarchical, dynamic, reusable, and unpredictable characteristics of HIS with virtual organization, category, and group perspectives. The virtual organization (VO) in this paper is regarded as a running subsystem or application. The members of a VO include all agents for completing the task of the subsystem or application. An agent may belong to more than one VO at the same time. Some previously developed agents can be reused by means of involving them in a new VO dynamically. The output of the *Reorganization Model* is the specification of the dynamic platform which comprises middle agents [3, 4] and makes all agents and agent groups hierarchical and dynamic. The *Design Model* gives the technical system specification in terms of application, architecture, platform, and ACL to concretize the outputs of the reorganization, coordination, and expertise models. The output of the design model can be implemented based on the different development environments.

3 Development of the System

The three development phases of the petroleum reservoir characterisation system are conducted by following MAHIS.

3.1 Conceptualisation Phase

Reservoir properties are a set of parameters which are usually used to recognise the geologic information in spatial variability. Lithology, permeability, and porosity are widely used to determine the oil well or field production rate of hydrocarbon. Well logs are a series of multi-type digital measurements along the vertical depth of drilled wells [5]. Understanding the form and spatial distribution of these heterogeneities is fundamental to the successful characterisation of petroleum reservoirs [6]. For identification of lithology and prediction of porosity and permeability, rock samples are obtained by using a coring barrel to recover intact cylindrical samples of reservoir rock. These samples are then sent to the laboratory and different petrophysical properties (porosity, permeability, etc.) and lithofacies are measured [7]. Well log readings (simply called well logs) are obtained every 150mm or so of depth, by lowering various sondes in the drilled wells. These measure formation and fluid properties in and around the wellbore location. Typical sondes generate electrical signals from measurements of radioactive, resistivity, acoustic, and neutron attenuation and scattering properties of the formation and its contained fluids. Because coring is a relatively time consuming and expensive process, much effort is made to relate other measures to the available core lithology, porosity, and permeability measurements so that the transformations developed can be applied to predict lithology, porosity, and permeability data in uncored wells or intervals [5].

However, a large amount of well logs, which were produced previously, faces to satisfy the current computer processing method. Before computers were widely applied in the petroleum industry, the well logs might be drawn on parameter graphs in curve mode [8, 9]. In the current computation environment, a novel system with the ability to digitise and manage those legacy well logs is required in the petroleum industry.

In petroleum reservoir characterisation system, a large number of shared data and components that interact in variational and complex ways are involved. This leads to complex behaviour that is difficult to understand, predict and manage. Take one sub-task of petroleum reservoir characterisation – the reservoir property prediction – as an example. We would like to give a typical scenario for the reservoir property prediction to indicate the concrete requirements. In order to identify which components should be contained in a typical petroleum reservoir characterisation system, without loss of generality, consider a geological research institute which provides the service to predict reservoir property. In such a place, there are an administrator, one personnel officer, some reservoir property prediction experts (decision makers), and several document keepers.

The parameter prediction process is initiated by a user contacting the administrator with new well logs and a set of requirements. The administrator asks the personnel officer to provide the experts' profiles, and then delegates each reservoir property to one or more experts based on the experts' profiles. The experts then work on the task and try to give their prediction results. When the experts make decisions, they may ask document keeper for checking some documents of the cored wells. After the experts finish preparing their prediction results (if one reservoir property was assigned to more than one expert, the prediction results from different experts must be combined to form a final one), they pass it to the administrator. Finally, the administrator sends the prediction results to the user.

From the petroleum reservoir characterisation requirements, we know that at least four processes need intelligent techniques. They are: well logs curve digitizing (*WLCD*), complicated lithology identification (*LI*), porosity prediction (*PP*), and permeability estimation (*PE*). If one reservoir property can be predicted by more than one intelligent technique, the predicting processes may include more than three in the system. At the same time, a combination process -- ordered weighted averaging (*OWA*) [10] -- must be added. The intelligent technique characteristics of those processes are summarised in Table 1. The intelligent techniques, namely, neural network, genetic algorithm, combination of fuzzy logic and neural network (FL and NN), and expert system, are selected.

Table1: The intelligent characteristics of the processes

Process	Characteristics	Intelligent technique
WLCD	if-then rules; inference; fuzzy set	Expert System
LI	Evolutionary computing, random parameter	Genetic Algorithm
PP	Uncertain prediction; matrix data	Neural Network
PE	Fuzzy set; uncertain prediction; similarity degree	FL & NN
OWA	if-then rules; inference; fuzzy set	Expert System

3.2 Analysis Phase

People in the petroleum reservoir characterisation system can be divided into three categories: user, managers (administrator and personnel officers), and service providers (well logs analysis expert, reservoir property predicting experts, and documents keepers). When a user wants to predict the reservoir properties based on some well logs, he/she usually goes to see the administrator in a geological research institute with the well logs. The first thing the administrator needs to do is to understand the user's work circumstances (UWC). The administrator may ask the user to provide the following information about UWC: his/her company, the location of the well where the well logs were produced, the sondes obtained the well logs, etc. Based on the information, the administrator will partition user's requirements as three kinds of tasks: lithology identification documents (LID), porosity prediction documents (PPD), and permeability estimation documents (PED). The administrator asks the personnel officer for available experts with LID, PPD, and PED. When the administrator gets the experts' profiles, he/she will delegate the user's requests to the experts. The experts predict the parameters according to the core well documents, users' uncore well documents, and their knowledge. At last, the administrator presents the results to user, after combining the experts' predictions.

According to the aforementioned descriptions, it is comparatively straightforward to identify the 11 tasks: *Image Pre-processing* (scans well logs as TIFF file; compresses the TIFF file), *Image Regeneration* (redraws well logs based on compressed or digitised data), *Curve Digitising* (tracks and rectifies well logs curves based on expertise), *Database Manipulation* (controls to operate database in agent environment), *Data File Manipulation* (controls to operate data files in agent environment), *Interaction with User* (controls to input user's requirements and to output results), *Properties Planning* (partitions the rock properties and makes them can be carried out), *Expert Searching* (searches which expert can do specific prediction task), *Prediction Delegation* (delegate specific prediction task to one or more experts), *Property Predictions* (completes predictions according to the experiences), and *Results Combination* (combines the multiple predictions of a property into one).

The agent model includes nine kinds of agents as described in Table 2.

Table 2: Agent model of the system

Name *(number)*	**Category**	**Group**	**Services**
Image Pre-processing *(1)*	Application	Curve Digitising	Carry out Image Pre-processing task
Image Regeneration *(1)*	Application	Curve Digitising	Carry out Image Regeneration task
Curve Digitising *(1)*	Service Provider	Curve Digitisation	Carry out Curve Digitising task
Middleware *(2)*	Service Provider	Middleware Agent	Carry out Database Manipulation and Data File Manipulation tasks
Interface Agent *(1)*	Application	Property Prediction	Carry out Interaction With User task
Properties Planning *(1)*	Application	Property Prediction	Carry out Property Planning task
Middle Agent *(4)*	Middle Agent	Middle Agent (1, 2)	Carry out Expert Searching and Prediction Delegation tasks
Property Predictions *(3)*	Service Provider	Intelligent Technique	Predict lithology and reservoir properties (porosity and permeability)
Results Combination *(1)*	Service Provider	Decision Aggregation	Carry out Results Combination task

All the agents in the petroleum reservoir characterisation system are divided into three categories: *application agent*, *middle agent*, and *service provider agent* in correspondence with the user, manager, and service provider in the organisation model. The application agent category includes some user's tasks and part of administrator's tasks. The agents in the application agent category are divided into two agent groups: curve digitizing and property prediction. There are several agents in each agent group. The middle agent category includes part of administrator's tasks and all tasks of personnel officers. Each group in middle agent category includes two middle agents and serves for one responsible group located in application agent category.

The service provider agent category includes part of administrator's tasks, all tasks of experts, and tasks of document keepers. The service provider agent category includes four agent groups: middleware agent (wrappers of database and data file server), reservoir property prediction agent, curve digitisation agent, and decision aggregation agent. Each group in service provider agent category includes different agents. In petroleum reservoir characterisation system, the agents in a group of the application agent category are asynchronous, but agents in the service provider agent category are synchronous.

Four agents (the lithology identification, the porosity prediction, the permeability estimation, and the curve digitizing) have employed intelligent techniques. These problem solving methods (PSMs) can be defined by CML as follows.

KNOWLEDGE-MODEL petroleum-reservoir-characterisation;
DOMAIN-KNOWLEDGE reservoir-properties-prediction-domain;
PSM-KNOWLEDGE psm-lithology-identification;
complicated lithology identification with parthenogenetic algorithm;
END PSM-KNOWLEDGE psm-lithology-identification;
PSM-KNOWLEDGE psm-porosity-predication;
porosity prediction with neural network;
END PSM-KNOWLEDGE psm-porosity-predication;
PSM-KNOWLEDGE psm-permeability-estimation;
permeability estimation with fuzzy neural network;
END PSM-KNOWLEDGE psm-permeability-estimation;
PSM-KNOWLEDGE psm-curve-digitising;
well logs curve-digitizing with expert system;
END PSM-KNOWLEDGE psm-curve-digitising;
END DOMAIN-KNOWLEDGE reservoir-properties-prediction-domain;

The platform of the petroleum reservoir characterisation system can directly employ PAHIS proposed in [2]. However, the categories, groups, and VOs should be defined accordingly. The VO will be automatically defined when an application is run. The members of a VO include all agents in an application group and relevant intelligent processing agents which are called by the running application.

The three categories can be organised with hierarchical structure as shown in Figure 1. The well logs curve digitizing and reservoir property prediction in application agent category are defined as two agent groups. There are several agents in each agent group. New application based on well logs information and reservoir property prediction intelligent techniques can be added into this category. Each group in middle agent category includes two middle agents and serves for one responsible group in application agent category. The number of the groups located in the application agent category is always same with the number of the groups located in the middle agent category. If an application is added into the system, a new group located in the middle agent category will be produced automatically. The service provider agent category includes four agent groups: middleware agent, reservoir property prediction agent, curve digitisation agent, and decision aggregation agent. Each group located in service provider agent category may include different number of agents. New developed service provider agents can be added into the system by means of advertising themselves to PAHIS and indicating which group the agents prefer. That is, the groups in this category are managed by middle agent rather than the service provider agent category.

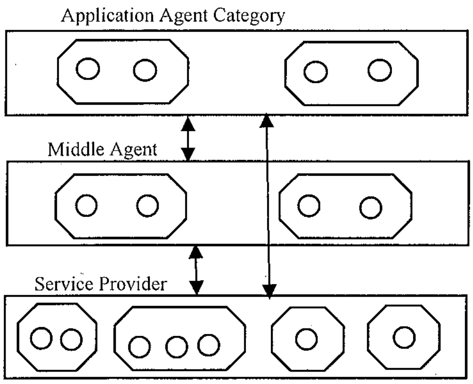

Figure 1: The hierarchical structure of the categories.

3.3 Design Phase

The first step to be conducted is the design of the system architecture. Because there are two application groups in the petroleum reservoir characterisation system, there are four middle agents (host 1, duplicate 1, host 2, and duplicate 2) in PAHIS in correspondence with the application groups: the well log curve digitizing and the reservoir property prediction. The middle agents are organised with the ring-based architectural model. Certainly, PAHIS supports more than two application groups added into the platform dynamically. Because middleware agents are used for manipulating database, a database-based agent communication language (DBACL) is proposed by enriching KQML

The DBACL is proposed by enriching the KQML primitive: *query*. The primitive query is defined as:

query
: sender <DatabaseAccessRequestAgent>
: receiver <MiddlewareAgent>
: content <DatabaseManipulationExpression>
: language C
: ontology Agent-database

The format of content is as following:

&$ITEM1:PARAMETER1_VALUE$$ITEM2:PARAMETER2_VALUE$......@

where "&" is the beginning mark of a database operation; "@" is the end mark of the database operation; "$" is the beginning and end marks of an item (statement). Each item includes three parts: parameter, its value and a separator ":".

There are two applications, well log curve digitizing and reservoir property prediction, in the petroleum reservoir characterisation system. The well log curve digitizing application completes well log curves digitizing and regenerating. The following agents must be employed for completing the two tasks: image pre-processing agent, image regeneration agent, and curve digitizing agent. Because well log curve digitizing application must interact with users, image pre-processing agent and curve re-generation agent manage the inputting information by keyboard, displaying states of the agent, image scanning, and displaying image on screen. The image pre-processing agent controls to scan well logs parameter graph into computer as image files (TIFF format) and save the image files as temporary image files to temporary file hard disk. Some images may need to be pre-processed for forming a standard image pattern before compressing and digitizing. And then the agent controls to compress standard image pattern files to data files, which will be stored forever in hard disk. At the same time, a large amount of hard disk space is saved. The curve digitizing agent digitizes the compressed image files (by tracking and rectifying). The image re-generation agent manages redrawing the well logs based on the compressed data files or digitized well log data.

The reservoir property prediction application completes lithology identification, porosity prediction, and permeability estimation. The following agents must be employed for completing the three tasks: lithology identification agent, porosity prediction agent, and permeability estimation agent.

4 Implementation and Results

Under the support of PAHIS, the prototype of the petroleum reservoir characterisation system has been implemented by using C language and Socket technique. When the platform of the system is initiated, all service provider agents and the application groups must register themselves to the platform first. The planning agent in the reservoir property prediction group has its own domain-specific knowledge base as well as meta-knowledge about when to use intelligent technique agents. The middle agent records the capabilities, ontology, names, group, etc. of all the service provider agents in a multi-agent system. The scenario goes as follows.

After the graph with well log curves is scanned as an image file by scanner, the image file is pre-processed as the standard pattern file and then compressed to characteristic data files, which are saved to data file servers by data file middleware agent. The curves implied in those data files can be digitized to curve data. Transmit curve data to middleware agent by means of DBACL to store the data to Oracle database. The re-generation agent which was developed for testing the results of curve digitizing can access curve data or other information in Oracle database or data files by means of middleware agents and redraw the well logs graph again. The agents worked well by processing test with thousands of well logs graphs.

About the reservoir property prediction, 118 stratum samples (column 3 in Table 3) located in a complicated block at Daqing Oilfield, China were processed by the system. Table 3 is part of the results related to lithology classification. The results are acceptable. It implies that agent-based hybrid intelligent technique is reasonable.

Table 3: Lithology stratum classification results

Class	Practical Lithology	Sampling Stratums	Matched Stratums	Precision
1	mudstone	24	22	0.928
2	siltstone	18	15	0.833
3	Argillaceous sandstone	21	15	0.714
4	shale	18	15	0.833
5	sandstone	27	25	0.936

5 Conclusion

The petroleum reservoir characterisation system has been developed by following MAHIS process stages. In conceptualisation stage, the requirements of the identification of lithology and the prediction of permeability and porosity were presented. At the same time, the hybrid strategy and intelligent techniques have been selected. In the analysis stage, the process organizational relationships, tasks, agents, groups, categories, VOs, interactions, and intelligent techniques have been clarified. The system's architecture, DBACL, and the components of applications have discussed in design stage. The petroleum reservoir characterization system has implemented based on PAHIS.

The Petroleum reservoir characterisation system has the following features: (1) the agents in application groups can easily access all parameter prediction agents, curve digitising agent, and middleware agents; (2) the agents in the service provider category can be added to or removed from the system dynamically; (3) the presence of PAHIS in this system supports the VO concept and makes the agents in the application category and service provider category reusable; (4) the legacy systems or resources can be used in agent environment by means of middleware agents; (5) Overall system robustness is facilitated through the use of the redundant middle agents with ring-based architectural model; (6) a database-oriented agent communication language is adopted by defining the content parameter of KQML.

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