A Cyber-Physical System for Semi-autonomous Oil&Gas Drilling Operations

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***Abstract*—In Oil&Gas drilling operations and after reaching deep drilled depths, high temperature increases significantly enough to damage the down-hole drilling tools, and the existing mitigation process is insufficient. In this paper, we propose a Cyber-Physical System (CPS) where agents are used to represent the collaborating entities in Oil&Gas fields both up-hole and down-hole. With the proposed CPS, down-hole tools respond to high temperature autonomously with a decentralized collective voting based on the tools' internal decision model while waiting for the cooling performed up-hole by the field engineer. This decision model, driven by the tools' specifications, aims to withstand high temperature. The proposed CPS is implemented using a multiagent simulation environment, and the results show that it mitigates high temperature properly with both the voting and the cooling mechanisms.**

I. INTRODUCTION

In its most recent report, the International Energy Agency (IEA) projects that oil consumption will grow in the upcoming decades, due to rising petrochemicals and trucking & aviation demand [1]. In Oil&Gas fields, a drilling rig is typically used to create a hole in the earth's sub-surface with a drill-string searching for natural resources. Once found, they are produced and then refined for public use. Until recently, low temperature wells constituted the large majority of existing wells because of the high manufacturing costs of high temperature tools due to the materials type and the manufacturing technology. Yet, low temperature wells are starting to be drained. Soon, there will be a high need for drilling high temperature wells. Nevertheless, the threshold for tools to withstand high temperature has not increased significantly (almost 15%). The high temperature of these wells damages the tools leading to additional costs caused by the time to go up-hole to change the damaged tool.

Investing in technologies to manage and mitigate high temperature showed to be cheaper than investing in a technology to withstand high temperature. Therefore, and to avoid the mentioned situations, sensors are attached to these tools in order to read their temperature. Moreover, measures are taken by the field engineer up-hole (several kilometers above the down-hole tools) to cool down temperature. In most of the existing systems, temperature mitigation up-hole relies only on one actuator which is *the mud cooler* to cool the drilling mud, which will be in contact with down-hole tools. However, this process has a long response time as the communication used between the down-hole tools and the up-hole field engineer is analogue, and it takes time for the cooled mud to reach down-hole. Moreover, in severe drilling conditions, the communication is unreliable as the analogue signal may be noisy or lost. In short, down-hole tools can sense danger but they cannot do anything to protect themselves and prevent damage.

In this work, we propose a Cyber-Physical System (CPS) [2] empowering the down-hole tools with a coordination mechanism to mitigate high temperature autonomously by controlling a down-hole actuator through a voting process. The tools are represented by agents that control the sensors and actuators embedded in these tools. Agents provide the features for a decentralized solution down-hole. They trigger a voting cycle to start a down-hole actuator aiming to mitigate high temperate in a decentralized manner waiting for the cooling performed up-hole by the field engineer. To implement the proposed CPS properly, a model of the drilling domain is constructed with all drilling mechanics and parameters, along with the well trajectory and temperature equations taken into consideration.

In our previous work [3], we have investigated the potential of building a near-real-time mitigation of high temperature while drilling using MAS. Our previous model overlooked the role of the field engineer that is responsible for the cooling of the drilling mud up-hole. Moreover, the tools voted with simple rules, i.e. without a specific decision model within the tool that uses a utility function to determine the desired actuator power level.

This work is organized as follows: Section II investigates the state-of-the-art. Section III discusses the proposed CPS. Section IV evaluates the proposed CPS and discusses the results. Section V draws the conclusions and states the future work.

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II. STATE OF THE ART

Since this work proposes a CPS for controlling drilling tools, Section II-A introduces a short background about the drilling operations. Next, Section II-B discusses the literature of CPS and MAS in the Oil&Gas industry. Finally, social choice theory, and particularly voting systems are studied in Section II-C.

A. Drilling Tools and Technologies

The Bore-hole Assembly (BHA) is a part of the drill-string that includes a set of drilling tools with embedded electronics used to drill the well (or bore-hole). Following are the main components from top to bottom of the BHA (Figure 1):

- **Measurements While Drilling (MWD):** It embeds steering & direction sensors that measure the position and direction of the tool compared to the Earth magnetic and gravity fields. Furthermore, it communicates with up-hole by transmitting data using a modulator. Data transmission methods vary, but the main method involves using pressure pulses in the mud system. However, successful data decoding up-hole is highly dependent on the signal-to-noise ratio, which is affected by the drilling conditions;
- **Logging While Drilling (LWDs):** used to measure -while drilling- the formation characteristics by relying on formation & evaluation sensors;
- **Rotary Steerable System (RSS):** used to steer the drilling BHA with continuous Rotation per Minute (RPM) of the bit;
- **Bit:** used to drill the formation.

All tools have repair & maintenance embedded sensors in them, which give the status of the tool and measure the temperature.

B. CPS and MAS in Oil&Gas industry

The role of CPS in the industrial applications has been discussed thoroughly in the literature [2] [4] [5]. Recent works proposed to increase the interaction between entities of the system in order to increase the competitiveness and achieve a transparent and efficient predictive manufacturing process [6]. However, their contributions are limited to the design principles, and no practical implementation was provided. Other research works discussed how, by utilizing advanced information analytics, networked machines will be able to perform more efficiently, collaboratively and resiliently. They specifically proposed a unified 5-level architecture as a guideline for the implementation of CPS [7]. However, the proposed architecture overlooked the heterogeneous aspects of the systems i.e. entities in the system may have different goals and specifications even though they are concerned with the overall goal of the system.

Agents are goal-oriented and software entities that are situated in some environment and capable of autonomous action [8]. The use of MAS for modeling in Oil&Gas drilling operations reduces the information load on human operators and provides a useful platform that pulls together simulation models as well as economic models. This platform helps in reaching a total asset solution and supporting employees in faster and more accurate analysis [9].

Most of the work in the MAS domain in Oil&Gas oilfields is still theoretical and conceptual. However, there are rare concrete applications. For instance, in [10], the authors discuss the scalability of Oil&Gas field production configurations, and present a novel application of MAS to facilitate intelligent multi objective control for maturing Oil&Gas fields. Moreover, Most of the work has concentrated on the supply chain and management aspects [11] [10]. No work addressed the processes of oil drilling and production. Despite the fact that some related works have shown that MAS can be used effectively while handling equipment [12], they did not inspect in detail the role of the CPS concepts in such systems.

C. Voting Systems in MAS

Social choice theory is a way to make a collective decision based on the possibly divergent opinions of the members of a community [13]. Voting is defined as a general, well-studied and well-understood scheme for preference aggregation [14].

Decentralized decision making problems can be solved with other techniques like Distributed Constraint Satisfaction Problems (DisCSP) [15]. Yet, with a small preference aggregation of choosing between discrete set of candidates where no complex calculations are required, voting systems are preferable as DisCSP can be compute-intensive. Thus, we opted for voting since we simply need a mechanism to aggregate a decision from the choices of all individuals.

In the domain of MAS, voting systems are an active area of research to enable decentralized decisions [16]. Agents are likely to represent different stakeholders with their own aims and objectives. This means the most plausible design strategy for an agent is to maximize its individual utility [17]. When different agents have different preferences within a MAS, it is desirable to have a mechanism enabling the agents to make a collective decision. Each agent expresses its preferences of the possible decisions, and a voting system aggregates these preferences to determine the collective decision [18].

III. THE PROPOSED CPS

This work proposes that tools down-hole mitigate high temperature autonomously with a decentralized collective decision through a voting process driven by the tools' specifications while waiting for the cooling performed up-hole by the field engineer. Notably, it takes advantage of the current equipment allowing for communication between these tools, as they all send measured/logged data to the MWD in order to send them up-hole using an actuator called *the modulator*. Additionally, *the bit controller* is an actuator down-hole in the RSS. It is responsible for controlling the bit rotation, that affects the speed of drilling. Reducing the speed means delaying the time to reach higher temperature. Even though this leads to a slower drilling, it mitigates the raise in temperature thereby saving the tools from damage and allowing them to drill deeper.

Section III-A analyzes the drilling mechanics and parameters. Section III-B discuses the multiagent and voting architecture. In addition, the agents features are outlined, and the tool agent decision model is discussed in detail.

A. Drilling Mechanics Model

In the literature of Oil&Gas domain, there is no concrete model of the drilling operations. The main purpose of this model is to represent the drilling mechanics needed for calculating the drilling speed properly and the increase in temperature while drilling that will eventually affect the tools.

In our previous work [3], concepts from the drilling terminology discussed in our model were introduced as follows:

1) Measured Depth (MD), measured by accelerometers in MWD, is the length of the hole, while True Vertical Depth (TVD) is the vertical distance from the surface until the bit. TVD is particularly important in determining the down-hole temperature, and is calculated from the MD and the drilling angle;
2) Temperature Gradient: the rate of increase in temperature per unit depth;
3) Drilling parameters: set by the field engineer and used to control the drilling process. Mainly, we focus on three crucial parameters:
    - **Force:** represented by Weight-on-Bit (WOB), it is applied to the drill-string, and only controlled up-hole.
    - **Rotation:** represented by Revolutions-per-Minute (RPM) of the drill-string, it is controlled up-hole but can also be modified down-hole in our CPS.
    - **Flow rate:** the mud flow rate circulating inside the drill-string to cool down the tools and carry cuttings resulted from the drilling process.

The speed of the drilling process or the Rate of Penetration (ROP) as a function of several parameters is shown in (Equation 1) [19].

$$ROP = K\frac{\overline{WOB}^{K}}{a^{p}}r \qquad (1)$$

Where K: a constant related to the formation hardness; $\overline{WOB}$: a function of WOB; r: a function of RPM; a^P: a function of flow rate and bit characteristics.

In the following, we will discuss the parts of the WOB, RPM and flow rate functions [19], while bit characteristics are not discussed as they do not change through out the run. The WOB function (Equation 2) is measured in (lbf) or (DaN) measuring unit. The RPM function (Equation 3 for hard formation and Equation 4 for soft formation) is measured in (cycle/minute) measuring unit. The flow rate function (Equation 5) is measured in (gallon/minute) measuring unit.

$$\overline{WOB} = \frac{7.88WOB}{d_b} \qquad (2)$$

Where d_b: bit diameter (in inch) which does not change in one drilling run.

$$r = e^{\frac{-100}{RPM^2}}RPM^{0.428} + 0.2RPM(1 - e^{\frac{-100}{RPM^2}}) \qquad (3)$$

$$r = e^{\frac{-100}{RPM^2}}RPM^{0.750} + 0.5RPM(1 - e^{\frac{-100}{RPM^2}}) \qquad (4)$$

$$F(FlowRate) = S\frac{P}{c} \qquad (5)$$

Where S: pump strokes measured in (strokes/minute) measuring unit; P: Pump rate for a stroke measured in (gallon/minute) measuring unit, which depends on the power of the pump; c: is a constant related to the efficiency of the pump.

B. The Multiagent and Voting Architecture

We propose in our CPS the use of MAS to represent the collaborating entities in the semi-autonomous Oil&Gas drilling operations both up-hole and down-hole (Figure 1).

In Figure 1 down-hole, each programmable tool in the BHA (MWD, LWDs and RSS) is represented with an agent. This agent is responsible for controlling the sensors and actuators embedded in the tool. Each tool has different sensors used to measure different types of data: Steering & direction data (MWD), repair & maintenance data (All), and formation evaluation data (LWDs). Only the MWD agent controls the modulator which is responsible for the communication with the field engineer up-hole. Similarly, only the RSS agent controls the bit controller that controls the bit rotation as per the result of the voting process down-hole.

In Figure 1 up-hole, the field agent represents the field engineer. This agent is responsible for controlling the drilling process by adjusting the drilling parameters when needed to drill ahead and reach the desired depth. Additionally, it controls the up-hole actuator i.e. the mud cooler. When the cooled mud goes down the hole inside the drill-sting, it will be in direct contact with all the tools down-hole.

Even though the existing drilling technology does not allow to control the bit rotation down-hole, we argue that the equipment to do so is already present in the RSS. The gain of decreasing the bit rotation is to slow down drilling and delay reaching a higher temperature. Meanwhile, down-hole tools send requests to the field engineer up-hole to increase the mud cooler power level.

1) The Agents Features:

In the following, we state the design goals and discuss the features of our agents:

Autonomous: In a real-time application like the one addressed by this work where the tools are down-hole with no humans, autonomy provides an added value. Yet, we consider that full autonomy of drilling operations is not needed. Instead, a trade-off should be sought in allowing to relieve the human field engineer from the burden of 24/24 monitoring while still permitting her to oversee the drilling process and intervene when necessary by both adjusting the drilling parameters and controlling the mud cooler.

Decentralized: The reason of the decentralization is threefold: First, the physical distance between the up-hole field engineer and the down-hole tools may go up to several kilometers. Second, data are sent from down-hole to up-hole in

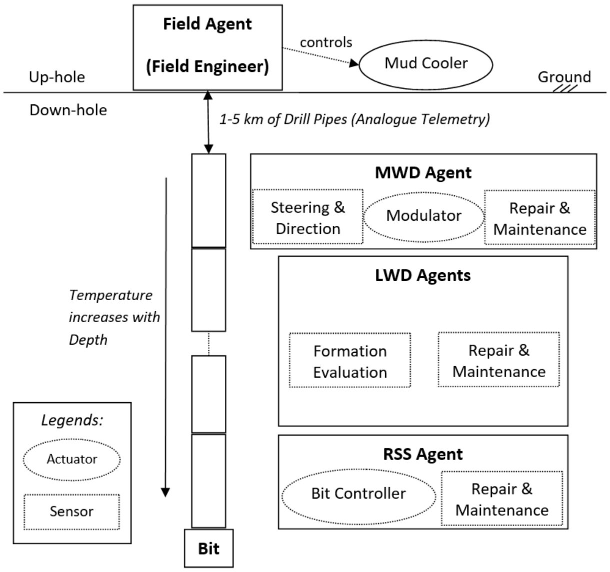

Fig. 1. The entities of the proposed CPS (based on our previous work [3]).

an analogue signal via the mud communication system. Hence, they are likely to be noisy or lost. More importantly, since the communication is slow, a significant delay is introduced and the data received up-hole reflect the state of the tools tens of minutes earlier. Third, each tool has different specifications to withstand high temperature and each tool has different actions to perform.

Reactive: Reactivity is an important requirement in real-time applications, and agents are reactive to the temperature they sense in the proposed CPS. Depending on the detected temperature level, the agent has different reactions as per the specifications of the tool.

Flexible (or Open): Tools can be added or removed arbitrary when the BHA is prepared up-hole between drilling runs. With this in mind, the use of agents is an efficient approach to achieve this requirement due to their intrinsic modularity. In other words, agents can be easily added or removed, without the need for detailed rewriting of the application. This feature also helps in preventing the propagation of faults, and in self-recovery. In addition, as the CPS is flexible in terms of tools chosen for a run, backup tools can be used instead of the failed tools already in run, which provides the CPS with a fault-tolerant feature.

Social: Agents can communicate with each other and with the physical components (sensors and actuators). This helps when an agent needs the action of another agent that controls an actuator (MWD, RSS, field agent). Moreover, each agent has different specifications to withstand high temperature. Therefore, there is a need for a mechanism to reach a collective decision for the benefit of the whole CPS, and we propose voting to handle this issue.

2) *The Tool Agent Decision Model:*

The temperature of the tool at specific time is determined by the depth and the geothermal gradient. It is the input of the decision model of the tool agent along with the temperature specification levels of the tool outlined as follows:

- **Danger Level**: when reaching this level, the tool starts to ask the MWD to control the modulator to communicate with the field agent up-hole to start the mud cooler.
- **Critical Level**: since the temperature of this level is near the tool's specification limit, when reaching this level, the tool reacts by starting a voting process down-hole.
- **Shutdown Level**: where the tool fails and gets damaged.

The decision model determines the bit controller power level desired by this tool agent. It is a number scaled between 0 and 100 representing a percentage power level of the bit controller. The utility function, used to output the desired power level is formulated as follows (Equation 6):

$$\frac{MaxP * (CriticalityRange - ToolShutdownLevel - ToolTemp)}{CriticalityRange} \tag{6}$$

Where:

- $MaxP$: the bit controller maximum power level;
- $CriticalityRange$: the subtraction of the average critical level of all tools from the average shutdown level of all tools. This value is constant for one drilling run, as the temperature levels (specifications) are fixed since the manufacturing of the tools. Only when different tools are used in different drilling runs, this value changes;
- $ToolShutdownLevel$: the current tool shutdown level;
- $ToolTemp$: the current tool temperature.

The desired bit controller power level is used to determine the final output of the model which is the vote of this tool agent. The ultimate goal is to strike a balance between maintaining a high ROP and preserving the integrity of tools by reducing the temperature.

IV. EVALUATION AND RESULTS

One of the challenges in the applications of Oil&Gas industry according to [20] is the huge complexity related to managing the assets that operate in the fields. Simulation environments provide a convenient alternative to test such applications. Therefore, the proposed CPS is evaluated using AgentOil [21] which is implemented using RePast Simphony [22], an agent-based simulation framework. The choice of this framework is based on a comparison of agent-based simulation frameworks showing that RePast Simphony has significant operational and executional features [23]. The drilling mechanics model is implemented as the environment in which the agents perceive, act and react. It allows for the agent decision models and the voting mechanisms implemented in the agents to be triggered and executed.

Section IV-A states the initial parameters of the experiments, and Section IV-B analyzes in detail the two parts of our CPS (voting and cooling) throughout the whole run time.

A. *Initialization and Parameters*

A simulation run represents a whole drilling run in real-life drilling process where the BHA is prepared at surface to drill the hole to a specific depth before the need to go back up to surface to replace the old tools in the BHA with new ones. All the simulation parameters have initial values that can be changed by the user at the beginning of the simulation.

Once the simulation starts, all agents are spawned in the environment. A simulation tick corresponds to one minute to normalize the results as speed is in m/min. In each tick, drilling parameters are measured (Equations 2, 3, 4 and 5) and the ROP is calculated (Equation 1). Therefore, the BHA drills and the temperature starts to increase with depth. Once the tools get their temperatures (from the TVD and the geothermal gradient), the decision model in each tool is considered, and requests to start actuators (up-hole and down-hole) are sent correspondingly to mitigate the high temperature. A simulation run can end either successfully (reaching the desired depth) or unsuccessfully (with a tool failure). Additionally, a complete log of the simulation run is provided in both cases.

The same number of agents were used in all experiments to normalize the results: Up-hole, one field agent (representing the field engineer); Down-hole, one MWD agent, three LWD agents, one RSS agent.

B. The effectiveness of the Cooling and Voting mechanisums

We investigate the behavior of the proposed CPS in real time (simulation ticks) to analyze its components and their direct impact in mitigating high temperature.

There are two mechanisms in our CPS to mitigate high temperature: First, starting the mud cooler up-hole to cool the mud. The mud cooler is controlled by the field engineer as per requests from down-hole tools sent to the field agent that represent the field engineer. Second, using the bit controller down-hole to slow down drilling. The latter is controlled by the RSS as per the voting choice of all down-hole tools. The vote of an agent is based on its internal decision model which takes the current temperature and the tool's specifications as inputs. Therefore, this experiment is divided into two parts: First, in order to assess the impact of the cooling mechanism, we turn off the voting mechanism. Second, the first part of the experiment is again replicated but with the cooling mechanism this time turned off and the voting mechanism turned on. Moreover, all runs are done with fixed WOB: 10k lbf.

In all the experiments, a temperature chart of one tool throughout the simulation is shown. In which, the x-axis represents time (simulation ticks), and the left y-axis represents temperature (degC). For the presented deep drilling run, the starting position is 3000 m, and the temperature corresponding to this depth is 99 degC.

1) The impact of cooling on temperature:

With the voting mechanism turned off, Figure 2 compares the temperature curve when cooling is enabled (blue curve) with the temperature curve when cooling is disabled (red curve) where the temperature is increasing linearly.

Since the beginning of the simulation, temperature increases with drilling. Notably, we can note that the blue curve started dropping compared with the red curve once the cooling mechanism was triggered at tick 238, that corresponds to the temperature 113 degC.

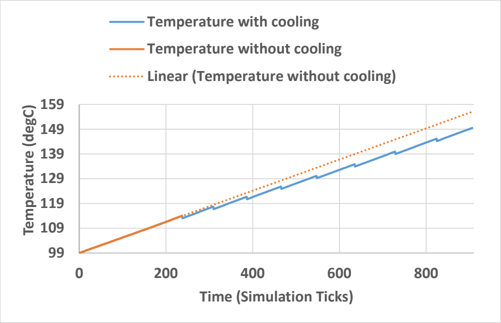

Fig. 2. Cooling effectiveness: temperature increase in time with and without cooling.

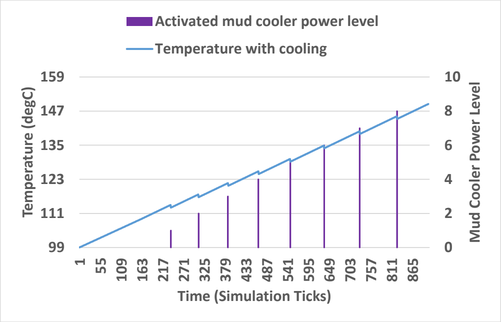

Fig. 3. Cooling effectiveness: Mud cooler power level impact on temperature.

In Figure 3, the right y-axis represents the mud cooler power level. At some moments, down-hole tools request the activation of the up-hole mud cooler when reaching the danger temperature level. Once the mud cooler power level is increased, the temperature witnesses a drop (first drop is at tick 238). It is important to remember that there is a delay between requests for cooling, as the signal takes time to reach up-hole and time for the cooled mud to reach down-hole. This explains the time delay between the temperature drop points.

2) The impact of voting on temperature: Turning off the cooling mechanism, in Figure 4, we can see the temperature curve with voting (blue curve) compared to the temperature curve with no voting (red curve), and we can notice that at the end there is a drop in the tendency of the temperature curve becasue of voting.

Figure 5 zooms in the chart (x-axis starts at tick 400) approximately at the time before the tendency drop of the temperature curve. In this figure, a new axis is presented (right y-axis), where we plot the bit controller power level elected by the voting mechanism. The voting started exactly at the tick 583 where a choice to start the actuator with 20% power level is taken. At the end and before the 150 degC, the maximum power level of the bit controller is used 100% and after that no more mitigation was performed till the failure of one tool.

It is important here to note also that triggering the voting mechanism (at critical temperature level) started after triggering the cooling mechanism (at danger temperature level),

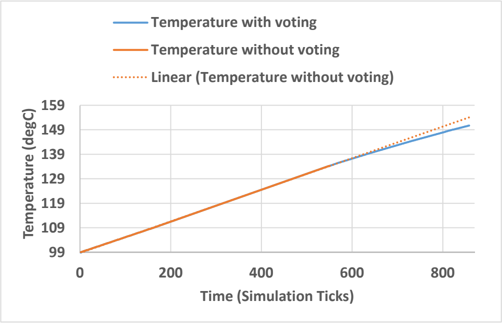

Fig. 4. Voting effectiveness: temperature increase in time with and without voting.

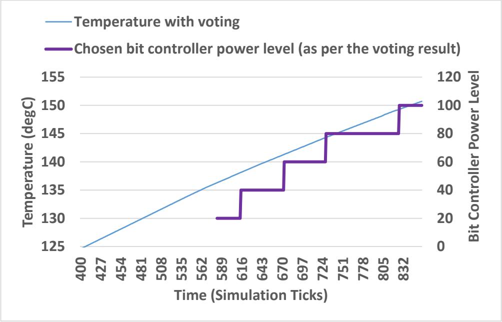

Fig. 5. Voting effectiveness: Bit controller power level impact on temperature.

hence there was more time for cooling to mitigate the temperature than for voting to do the same.

V. CONCLUSION AND FUTURE WORK

In Oil&Gas drilling operations and after reaching deep drilled depths, a significant increase in the temperature damages the down-hole tools. To handle this issue, this work proposed a CPS where agents are used to represent the collaborating entities that can control sensors and actuators both down-hole and up-hole. In the proposed CPS, the process to request for the cooling performed up-hole by the field agent that represents the field engineer or to cast the vote down-hole to start the bit controller are governed by the decision model of each tool agent. The results show that our CPS mitigates high temperature with both the voting and the cooling mechanisms.

As a future work, we believe that Explainable Artificial Intelligence (XAI) has a significant role in our model. Given that we operate in a semi-autonomous system in which the human field engineer undertakes a less tedious, but still a commanding role, defining the communication process between humans and the other entities of the CPS (tools, sensors and actuators) is key to help the engineer understand the decisions of the CPS. Additionally and as some tools are more important than others due to the services they provide and the roles they play, we plan to extend our model to emphasize this fact by implementing the concepts of weighted voting.

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