AUTOMATED CLASSIFICATION SYSTEM FOR PETROLEUM WELL DRILLING USING MUD-LOGGING DATA

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Abstract. *During the petroleum well drilling operation many mechanical and hydraulic parameters are observed by an instrumentation system installed in the rig named mud-logging system. The mud-logging system is composed by several sensors distributed in the rig; these sensors measure different operation parameters like: hook load, column rotation, mud pit level, pumping pressure, etc. The mud-logging system allows to track the evolution of each measured parameter on-line. Nowadays, many parameters are continuously measured in the mud-logging units with a supervising purpose. However, in the most of cases, those data are stored without take advantage of all its potential. In other hand, to make use of the mud-logging data, it is required analyze and interpret it. That is not an easy task because of the large amount of information involved. This work presents a system that can automatically classify the operation stage that is being executed using mud-logging data interpretation. The system allows to classify for instance if the rig is in a rotary drilling process, or if the rig is circulating mud in the well, etc. The here presented system was used to classify two days of an offshore well drilling operation. In order to check the performance of the system, the results obtained were compared with the expert handmade diary drilling report classification. It was observed a high level of conformity between the system classification and the drilling report classification mainly in small time periods where the drilling report classification is more precise. For larger periods of time, the automated system obtained a more precise classification because it make possible to individualize each executed stage. The proposed system allows the online classification of stages or the stages classification from a drilled wells database. The system can also be used to develop a tool able to automatically generate a precise record of the executed stages.*

Keywords*. Offshore Drilling, Mud-logging, Measurement System, Automated Systems.*

1. Introduction

Offshore petroleum well drilling operation is an activity that usually involves high cost and complexity. It demands a high qualification level of drilling experts. Nowadays, there is a great concern about the optimization of drilling activities with the purpose to guarantee the drilling execution in a safety and low cost manner.

In the last two decades, the technological advances in drilling techniques has contributed considerably to reduce costs and to enlarge exploration areas. The improvement of Directional Drilling, Measuring While Drilling (MWD) and Logging While Drilling (LWD) Systems and the development of drilling capabilities for deep and ultra-deep water are evidences of how technological progress has changed the petroleum exploration scenario.

Technological progress in petroleum engineering field was in part motivated by the evolution in instrumentation techniques, which affected not only the petroleum exploration but also the field development and production activities. As result of increasing instrumentation level, today, large amount of well drilling operational data has been measured and recorded. However, techniques of data interpretation and evaluation have not developed at the same speed, and there is a lack of tools able to make an efficient analysis and use all data and information available.

This work presents the development of a system that uses the information collected by mud-logging techniques during well drilling operations. Nowadays, the mud-logging techniques do collect huge amount of data. However, much of the valuable information is not being used as much as it should be. The main goal of the proposed system is to take advantage of potential valid information contained in the database, which is not being completely exploited. The output of this exploration could be used to produce performance enhancement.

The proposed methodology is able to generate a precise report of the executed stages during an operation through the interpretation of mud-logging data. It has two possible applications. The first one is related to the performance analysis and abnormalities investigations. In this sense, the developed tool could be used to carry out later analysis of the time spent in drilling each well in a field, and to investigate how much each stage consumed from the total operation time. The second one is that the methodology could be implemented in a computer system to produce on-line report of the executed stages in the rig, and this report would present the same time precision as the mud-logging data.

Similar initiatives for development of automated supervising systems in other fields were observed for mining engineering problems (Yue *et al.*, 2003).

The presented work was developed at Unicamp, in the Lab of Artificial Intelligence Applied to Petroleum (LIAP). LIAP team has been working in the last years developing intelligent and automated systems for oil and gas industry (Mendes et al., 2001 and Silva *et al.*, 2003).

2. Mud-logging System

During the petroleum well drilling operation many mechanical and hydraulic parameters are measured and monitored in order to perform the drilling in a safe and optimized manner. There are many systems that work together in a rig to accomplish this task. One of these systems is named mud-logging and it is responsible for measuring and monitoring a set of mechanical and geological parameters.

The use of mud-logging systems was introduced in Brazil in the 70 decade. At that time, only a reduced number of parameters were monitored. Since the 70s, with development in instrumentation techniques, the number of measured parameters has increased and the use of mud-logging systems became a common practice in the oil industry.

Another aspect that contributed to the progress of mud-logging techniques in Brazil was the development of deep and ultra-deep water drilling technologies. The deep and ultra-deep water environments require a very accurately controlled drilling operation. Any failure or negligence may cause great human and economic losses. To have a process controlled with accuracy, it was needed to improve available information systems. In this context, the mud-logging was enhanced to become an important information system.

Nowadays, mud-logging systems have two distinct dimensions, the first one is responsible for collecting and analyzing formation samples (shale-shaker samples), and the second one is responsible for measuring and monitoring mechanical parameters related to the drilling operation. Considering only the second dimension, the mud-logging system could be characterized as a complete instrumentation system.

To accomplish its mission, mud-logging systems in general rely on a wide range of sensors distributed in the rig operative systems. One important characteristic of this technique is that there is no sensor inside the well, and the measurements are made on the rig. The data collect by the sensors is then sent to a central computer system, where the data is processed and displayed in real time through screens installed in the mud-logging cabin and in the company-man office. The checking of the parameters evolution is made by display devices; the system allows the selection of displayed parameters as well as the selection of its presentation appearance (numbers or graphics). During all the drilling operation, there is an operator watching the parameters alert to any kind of abnormality. If an observed parameter presents an unusual behavior, the operator communicates immediately the driller that will carry out properly procedures to solve the problem. Actually, the system allows the programming of alarms that will sound in the mud-logging cabin, alerting the mud-logger that the value of the observed parameter is outside of the programmed range.

The number of observed parameters may vary according to the particular characteristic of the drilling operation. The most common measured parameters are: Well Depth (Depth), True Vertical Depth (TVD), Bit Depth, Rate of Penetration (ROP), Hook Height, Weight on Hook (WOH), Weight on Bit (WOB), Vertical Rig Displacement (Heave), Torque, Drillstring rotation per minute (RPM), Mud Pit Volume, Pump Pressure, Choke Line Pressure, Pump Strokes per minute (SPM), Mud Flow, Total Gas, Gas Concentration Distribution, H_2S concentration, Mud Weight in/out, Drilling Fluid Resistivity, Drilling Fluid Temperature, Flow Line, LAG Time, and Stand Length.

It is noticed that only some of listed parameters are really measured using sensor devices. Some of them are estimated from measured parameters. The WOB, for instance, is an estimated parameter. It is calculated using the WOH (a measured parameter) and the weight of drillstring elements.

In following, a sequence of pictures taken onboard of an offshore floating rig shows examples of mud-logging system application.

Figure 1 shows the sensor that measures the hook height. In the presented situation, the hook height is being measured through the drawworks revolution. It can be noticed, using Fig. 1, that there is more than one sensor device installed. It has occurred in this specific case because, besides the mud-logging sensor, there is also the rig and the MWD sensors.

Figure 2 presents the sensor for hook weight measurements. In the presented situation the weight is being measured by strain gauges installed in the deadline. As mentioned before, this measurement is utilized to calculate the WOB.

Figure 3 presents a sensor installed close to the mud pump piston. It measures the number of strokes in a time unit. The mud flow rate is calculated using the number of strokes, the geometry of the pump chamber, and the pump efficiency. Actually there is more than one pump operating at the same time, and the total mud flow rate is obtained from the summation of individual flow rate of each pump.

Figure 4 presents the choke line pressure sensor. This sensor device is installed in the choke manifold at the rig floor.

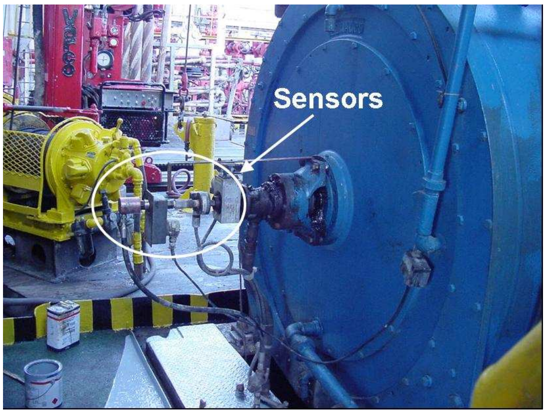

Figure 1. Assemble of the hook height sensor at the drawwork.

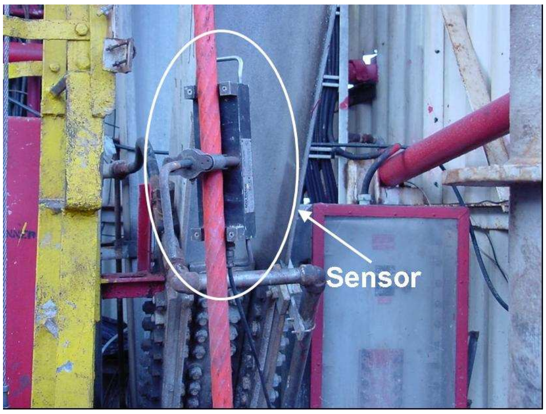

Figure 2. Assemble of the hook weight sensor at the deadline.

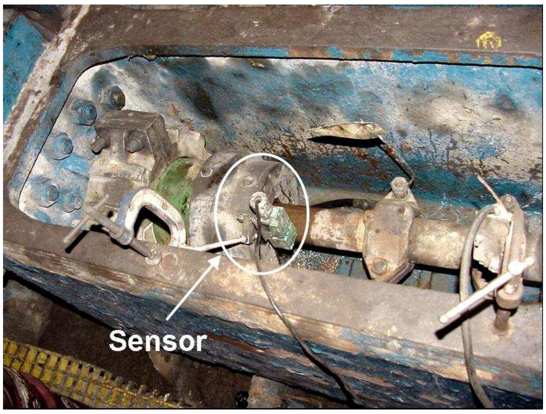

Figure 3. Assemble of the strokes sensor at the pump piston.

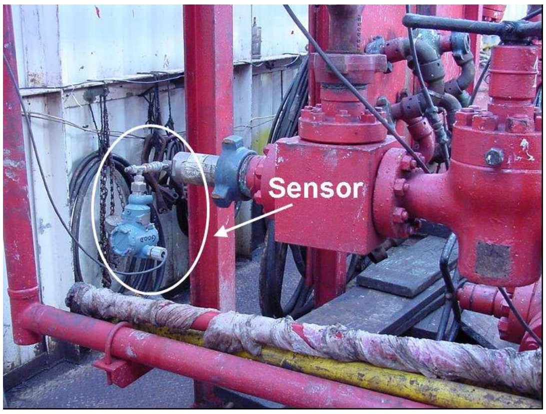

Figure 4. Assemble of the pressure sensor at the choke manifold.

A main function of mud-logging system is the early kick detection based on observation of mud pit volume, mud weight, and shale density. The mud-logging data can also be used to monitor the formation pore pressure and the formation fracture gradient. The formation pore pressure can be estimated using correlations that involve drilling parameters like Weight on Bit (WOB), Rate of Penetration (ROP), Mud Flow, etc.

The mud-logging monitoring services are generally provided by a specialized company. At the end of a drilling operation, the company makes a report relating occurrences associated to the completed operation. During the drilling parameters monitoring, a huge amount of data is usually generated. Due to difficulties of data storage, these data are summarized into smaller files. The common practice is to reduce the sampling frequency of the measurement from second basis to minute. If it solves the problem of file sizes, on the other hand it represents a lost of great amount of information. There are some events that may occur and last only few seconds, like the drag occurrence in tripping out. When the data is summarized the information about the drag occurrence could partially be lost.

Another important question related to mud-logging system is the redundancy of measured parameters. Besides the hook height, others parameters have been usually measured by more than one instrumentation system. It is common to find rigs where the same parameter is being measured by the mud-logging company and by the rig system itself. And it is not rare to observe cases where the measurements taken do not show the same absolute value. This behavior has raised discussions about the future of mud-logging system.

The general observed tendency is that the latest generation rigs have high level of instrumentation. In this context, probably, the onboard rig measurement system will be responsible for measuring and monitoring all drilling parameters while the mud-logging services will be restricted to shale-shaker samples analysis.

The following section presents the description and construction of the proposed automated classification system.

3. The Classification System

3.1. Individual stages associated to the drilling operation

The drilling of petroleum well is not a continuous process constituted by one single operation. Looking to it with a small scale it is possible to notice that the petroleum well drilling operation is made up by a sequence of discrete events. These events comprised in the drilling operation will be named here as drilling operation stages.

Six basics stages associated to the drilling operation were identified to build the proposed classification system. Table 1 presents a brief description of each considered stage and the labels adopted.

Table 1. Description of the considered stages.

Mode	Drilling Operation Stages	Label
Rotating Mode	**Rotary Drilling:** In this stage occurs the drilling itself; the bit really advances increasing the well depth. The drillstring is rotating and there is mud circulation. The drillstring is not anchored in the rotary table causing a high hook weight level.	RD
	Reaming: In this stage despite the high hook weight level, the mud circulation and the drillstring rotation, the bit does not advance increasing the final well depth. In this situation there is a reaming of an already drilled well section.	RR
Non-Rotating Mode	**Drilling (Sliding Drilling):** In this stage, the bit really advances increasing the well depth. The difference here is that the drillstring is not rotating and the drilling occurs due to the action of the downhole motor. There is mud circulation and a high hook weight level.	NRD
	Reaming or Tool Adjusting: In this stage the bit does not advance increasing the final well depth. There is circulation and a high hook weight level. This condition indicates that a reaming cycle is being executed or that the tool-face of the downhole tool is being adjusted.	NRRA
-	**Tripping:** This stage corresponds to the addiction of a new section to the drillstring. The drillstring is anchored causing a low hook weight level. The drillstring does not rotate.	T
-	**Circulating:** In this stage there is no gain in the well depth. It is characterized by fluid circulation, high hook weight level and a moderated rotation of the drillstring.	C

The described above six stages represents a first effort to individualize the basic stages of a drilling operation. The stages were detailed considering the drilling phases with mud return to the surface. The drilling technology considered was the drilling using mud motor and bent housing. This classification may not be satisfactory to the initial drilling phases and for special operations, like fishing, in the well. In the same way, if other drilling technologies are considered, small adjustments in the stages definition will be required. For instance, using rotary steerable systems, it doesn't make sense to make distinction between rotary drilling and oriented drilling stages as they were defined in the presented work, because these systems are supposed to drill all the time using drillstring rotation.

3.2. Architecture of the Classification System

In order to identify the stage that in being executed, the system need some of the information monitored by the mud-logging system. This work suggests the use of four parameters: Bit Depth, Weight on Hook – WOH, Stand Pipe Pressure – SPP and Drillstring Rotation – RPM.

After reading the information; the data are interpreted according to a set of pre-established rules. As result, the system will associate an operation stage to each set of data according to the rules.

The classification obtained using the system could be used to automatically generate a logging of the executed stages. Figure 5 presents an illustration of the system architecture.

It is important to notice the parameters reading can be done either from previous stored mud-logging files or from mud-logging systems in real time. It means that the system could be used either to carry out classification in a database of drilled wells or to generate an on-line report in the rig.

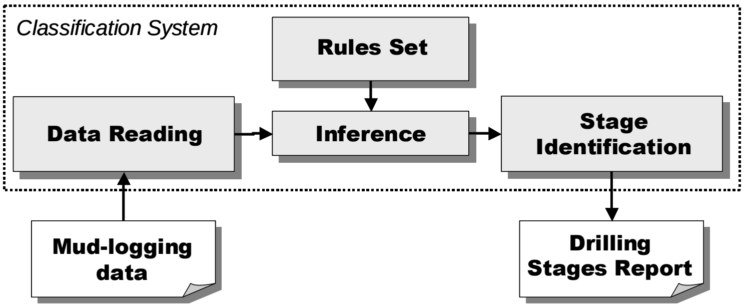

Figure 5. Architecture of the Classification System.

The automated processing of the data is vital due to the great volume of information involved. If we consider a sampling data second by second, for just one hour of operation would be produced 14400 (4 x 3600) parameters value what makes the manual classification a very time consuming task.

The system knowledge is represented by a set of rules. In this sense, human knowledge was represented in a programmable language. In this work, the operational knowledge is represented by a set of If →Then rules.

In order to build these rules, human knowledge regarding characteristics of each stage and the relation of each stage with the four parameters measured by the mud-logging system was required. From the relation between stages and chosen parameters six independent rules were formulated, resulting then in one rule for each stage. Table 2 presents the rules used in this work.

Table 2. Considered rules.

Operation		**Bit Depth**	**RPM**	**WOH**	**SPP**	**Classification**
Rotating Mode	Drilling	Positive variation, and bit depth equal or larger than the maximum depth	High	High	High	Rotary Drilling - RD
	Reaming	Positive, negative or null variation, and bit depth smaller than the maximum section depth	High	High	High	Rotary Reaming - RR
Non-Rotating Mode	Drilling	Positive variation, and bit depth equal or larger than the maximum depth	Null	High	High	Non-Rotary Drilling - NRD
	Reaming or Toll Adjusting	Positive, negative or null variation, and bit depth smaller than the maximum section depth	Null	High	High	Non-Rotary Reaming or Tool Adjusting - NRRA
Tripping		Null variation	Null	Low	Low	Tripping - T
Circulating		Smaller than the maximum depth	Null	High	High	Circulating -C

The stage "Tripping", for instance, is characterized when there is no well depth variation, no drillstring rotation, and there is low hook weight and low pressure levels in the stand pipe.

The labels "High", "Low" and "Null" used in Tab.1, actually correspond to a range of values. The ranges vary according to the rig and parameter considered. For example, for a particular rig, a High WOH level can be a value above 250 klbs, while a Low level would be a value below 250 klbs.

The rules presented in Table 2 are a first effort to build a more complex system able to classify a larger quantity of stages. If additional technical knowledge about stages is added, it will make possibly to obtain a more refined set of rules able to classify more stages.

4. Results

The proposed system was tested with real mud-logging data from a database. In this database data are summarized per minute, then for each parameter only one value for each minute is available. The first presented result is the classification obtained for seven hours of drilling operation in an offshore well.

The results are presented in Figure 6 in order to make easy the understanding. The considered mud-logging information is presented in the four first time records. The first record, for instance, presents the Bit Depth parameter. The vertical axis represents the Bit Depth and the horizontal one represents the time in minutes.

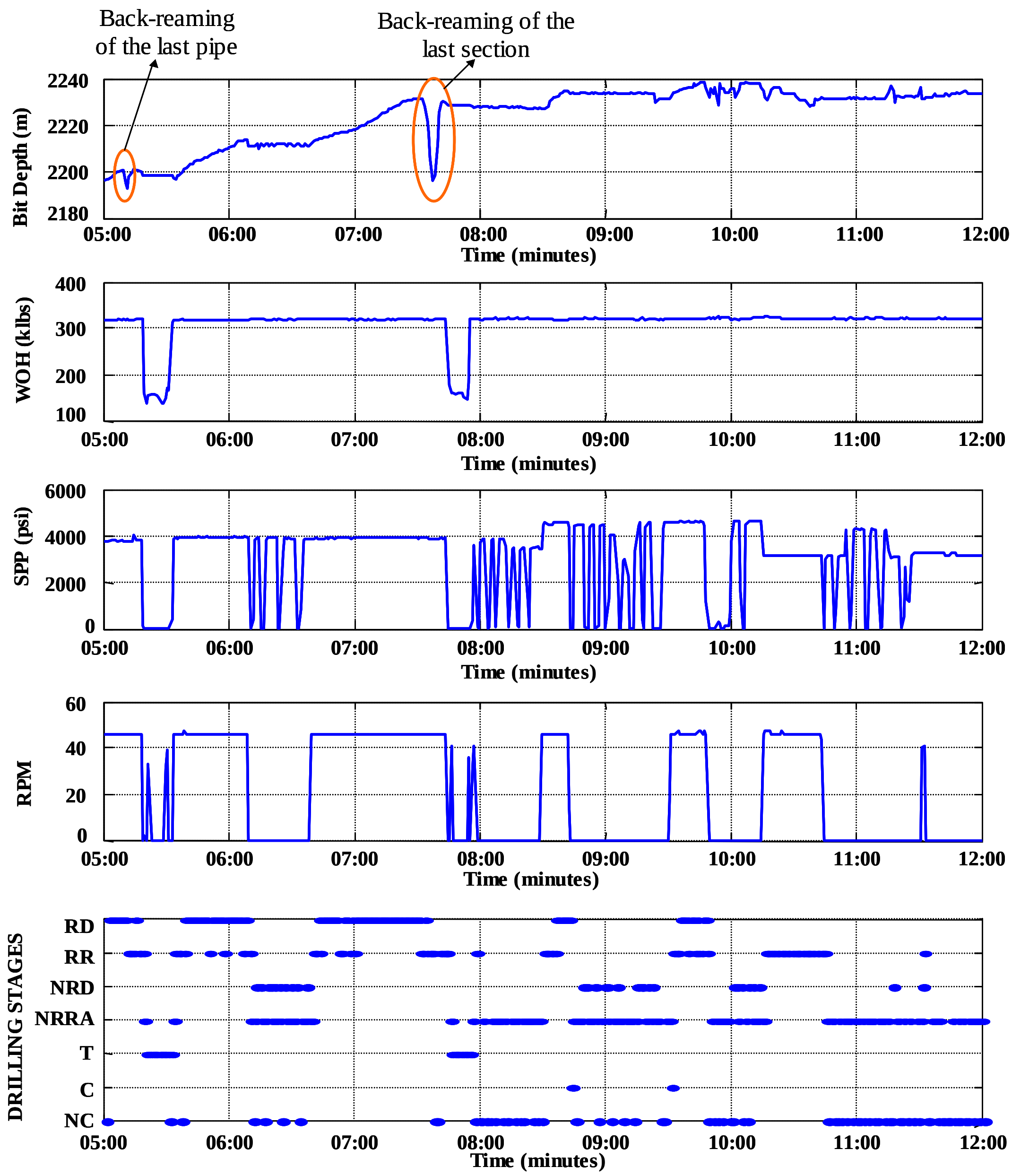

Figure 6. The classification produced by the system for seven hours of drilling operation in an offshore well.

The last time record in Figure 6 presents the system classification. The horizontal axis represents the time and the vertical axis represents the resulted classification. The classification is indicated in the vertical axis using the labels defined in Tab. 1 and the additional label “NC”, which indicates not classified data. Each horizontal line represents one stage. Observing the line identified by the label “T” (Tripping), it can be noted that just two “Tripping” were executed during the considered period, one in the first and other in the third measured hour. The examination of the “NRRA” (Non-Rotary

Reaming or Tool Adjusting) line shows that a significant fraction of the total considered time was spent in this stage. It can be explained by the characteristic of the drilling technology employed. When a directional well is drilled using downhole motor and bent housing, much time is spent trying to set the tool-face angle, and this time is computed as “Non-Rotary Reaming or Tool Adjusting” time, according to the definitions presented in Tab.1.

From the same Figure 6, other important feature can be observed. In the classification and inspecting the first record, it is possible to observe that before the first tripping only the back-reaming of the last pipe was executed, while before the second tripping it was executed the back-reaming of all the last section. This is an example of what kind of information is “hidden” in mud-logging data.

The second obtained result is the classification for two days of drilling operation in another offshore well. In order to check the performance of the automated classification system, the two days of the system classification were compared with the classification registered in the Daily Drilling Report (DDR) of the considered well.

The DDR is an operational report elaborated by a company expert responsible to supervise the drilling operation; this report is filled up at the end of every day onboard the offshore rig. The DDR presents a low level of standardization; the DDR operation descriptions are very influenced by the person responsible to complete the report. It is common to find DDRs where the details of the descriptions suddenly change from a given day to another. It is a direct result of the change of the company drilling expert in charge. It can be said that each company expert has an individual style to complete DDR; some of them are more detailed while others are more concise.

Table 3 presents part of the results obtained for the comparison between the automated system classification and the DDR records.

Table 3. Comparison between the automated system classification and the DDR classification.

LINE NUM.	**DAILY DRILLING REPORT**					**AUTOMATED CLASSIFICATION SYSTEM**						
	DATE	FROM	TO	TIME PERIOD (h)	DDR DESCRIPTION	ROTARY MODE		NON-ROTARY MODE		T	C	NOT CLASSIFIED
						RD	RR	NRD	NRRA			
01	07/09/2003	7:00	9:30	2.5	NON-ROTARY DRILLING	37%	5%	33%	19%	3%	0%	3%
02	07/09/2003	9:30	11:00	1.5	ROTARY DRILLING	73%	8%	3%	9%	6%	1%	0%
03	07/09/2003	11:00	12:00	1	NON-ROTARY DRILLING	22%	5%	43%	23%	2%	0%	5%
04	07/09/2003	12:00	12:30	0.5	ROTARY DRILLING	80%	3%	0%	17%	0%	0%	0%
05	07/09/2003	12:30	14:00	1.5	NON-ROTARY DRILLING	0%	12%	0%	78%	4%	0%	6%
06	07/09/2003	14:00	15:00	1	ROTARY DRILLING	28%	18%	33%	20%	0%	0%	0%
07	07/09/2003	15:00	16:00	1	NON-ROTARY DRILLING	0%	0%	50%	38%	7%	2%	3%
08	07/09/2003	16:00	17:00	1	ROTARY DRILLING	40%	10%	17%	33%	0%	0%	0%
09	07/09/2003	17:00	18:00	1	NON-ROTARY DRILLING	0%	0%	27%	58%	10%	0%	5%
10	08/09/2003	18:00	19:30	1.5	ROTARY DRILLING	40%	17%	27%	16%	0%	1%	0%
11	08/09/2003	19:30	21:00	1.5	NON-ROTARY DRILLING	16%	3%	50%	22%	4%	0%	4%
12	08/09/2003	21:00	23:00	2	ROTARY DRILLING	53%	18%	0%	25%	3%	1%	1%
13	08/09/2003	23:00	0:00	1	NON-ROTARY DRILLING	17%	8%	50%	23%	2%	0%	0%
14	08/09/2003	0:00	0:30	0.5	ROTARY DRILLING	40%	27%	0%	17%	17%	0%	0%
15	08/09/2003	0:30	1:00	0.5	NON-ROTARY DRILLING	20%	0%	57%	23%	0%	0%	0%
16	08/09/2003	1:00	1:30	0.5	ROTARY DRILLING	27%	3%	27%	43%	0%	0%	0%
17	08/09/2003	1:30	2:00	0.5	NON-ROTARY DRILLING	0%	0%	60%	23%	13%	0%	3%
18	08/09/2003	2:00	2:30	0.5	ROTARY DRILLING	37%	23%	3%	37%	0%	0%	0%
19	08/09/2003	2:30	3:00	0.5	NON-ROTARY DRILLING	0%	0%	77%	20%	0%	0%	3%
20	08/09/2003	3:00	3:30	0.5	ROTARY DRILLING	30%	3%	13%	33%	0%	0%	20%
21	08/09/2003	3:30	4:30	1	NON-ROTARY DRILLING	3%	7%	53%	25%	7%	0%	5%
22	08/09/2003	4:30	5:00	0.5	ROTARY DRILLING	60%	7%	13%	20%	0%	0%	0%
23	08/09/2003	5:00	5:30	0.5	NON-ROTARY DRILLING	0%	0%	73%	23%	0%	0%	3%
24	08/09/2003	5:30	6:00	0.5	ROTARY DRILLING	27%	20%	13%	30%	0%	0%	10%
25	08/09/2003	6:00	6:30	0.5	NON-ROTARY DRILLING	0%	0%	53%	17%	3%	0%	27%

From the Table 3, it is possible to observe that DDR records and the classification of the proposed system become close each other, in general, when the time period considered is short. Considering the line number 01 (period of 2.5 h), it can be noted that the DDR classification is “Non-Rotary Drilling” for the entire interval, while the automated system classification indicates that 33% of the time was spent in “Non-Rotary Drilling”. Considering the line number 15 (period of 0.5 h), the DDR classification indicates “Non-Rotary Drilling” for the entire period, while the automated system indicates that 57% of the period was spent in “Non-Rotary Drilling”.

This behavior can be explained by the fact that the DDR provides more exact information when time intervals are shorter. When time interval is long, commonly more stages are comprised in the time interval. The problem is that the executed stages are not properly registered in the DDR. The common practice is the company expert classifies longer intervals with the operation that he believes to be the more important (for example, that one consumed longer period of time, or that one produced more positive results). Consequently, part of the information about the executed operation is lost and it can not be recovered from the DDR.

The lines 16 and 20 in Table 3 are examples of the poor DDR classification. Both lines are classified as "Rotary Drilling" by the DDR, but according to the mud-logging data the time spent with RD was 27% and 30 % respectively. In these two cases most part of the time was consumed by Non-Rotary Stages and it is not registered in the DDR. In general, the expert classification "Rotary Drilling" includes the two Rotary Mode Stages (RD and RR), but even this consideration does not make DDR classification suitable.

The proposed system allows automatically classify the executed stages and the time consumed by each stage. If the accuracy and the detail level are considered, it can be concluded that the proposed system provides significant advantages if compared with the DDR.

Table 3 also shows that a small percentage of data was not classified. It can be explained by two factors. The first one is the quality of mud-logging data. The presence of outliers, probably caused by mistakes in the measuring process, was observed within the data during the development of the presented work. With the purpose to minimize the influence of these mistakes, the system makes use of measured variation (instead of measured value) always it is possible. It is available in the literature, discussions regarding mud-logging data quality and its quantitative use limitations (Kyllingstad *et al*., 1993).

The second factor that can explain the presence of non classified data is the consistency of the adopted rules. The rules were formulated considering that for each stage there is a particular parameter configuration. The problem is that the parameters do not necessarily change at the same time. For example, considering the "Tripping" stage, the "column anchor" and the "pumps turn off" do not occur exactly at the same time. A delay may occur, and during this delay an unexpected parameters configuration is characterized. The unexpected configuration results in "not classified" data.

Improvement in the quality of data and improvement of the rules can increase the classification level.

5. Acknowledgements

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6. Conclusion

The development of an automated classification system for basic stages of drilling operation was presented. This system represents an initial effort to build a more complex system able to classify a larger set of stages and to generate automatically operational reports using mud-logging data. The classification system presented can be used either to classify stored mud-logging data of a drilled wells database or to classify mud-logging data on-line and onboard in a rig. Due to the detailing level regarding executed stages provided by the classification system, it can be helpful to analyze the individual drilling performance of each well. Information about the total time spent in each stage combined with related economic costs can be used to assess the real cost reduction benefit caused by optimized drilling programs and introduction of new technologies.

Information concerning individual drilling performance can be used also to build benchmarking analysis. In this sense, a petroleum company could use this information to carry out comparisons between performances of different divisions. In a minor scale, the company could compare rented rigs performances and identify weak points as part of ongoing improvement process. The results produce by the proposed system may give support to the design of new wells. The information about the time spent to execute a determined stage could be used for planning new wells in the same region providing cost estimations.

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