Design Principles Behind the Construction of an Autonomous Laboratory-Scale Drilling Rig

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Abstract: In recent years, hot topics such as digitalization, machine learning, digital twin and big data have evolved from being envisions on the paper to state of art solutions, expected to revolutionize drilling efficiency in the industry. Drilling automation tomorrow is all about exploiting the current state of technologies available to the entire operation of drilling a well. Not only can drilling automation limit costs and reduce the risk to rig personnel and the environment, but they also give access to locations of considerable potential that previously have been regarded unsafe or uneconomical to operate in. There are however some challenges in keeping up with the ever-increasing pace of the development. For one, testing of novel and innovative solutions is often very expensive because of non-productive rig time during implementation, trial runs and data evaluation. Also, the modern technologies require extensive R&D before on-site testing can even commence. While on land-rigs, some of these costs and risks can be greatly minimized, many offshore solutions lack that luxury. This paper presents an overview of the design principles that go into the construction of a fully autonomous laboratory-scale drilling rig at the University of Stavanger. It aims at describing 1) the engineering principles involved to resemble full-scale drilling operations on the laboratory scale, 2) design considerations and components, 3) component requirements for the rig, 4) control system algorithms for real-time optimization of drilling parameters and detection and handling of drilling anomalies, 5) development of drilling models (drill string dynamics, bit-vibration, etc.) and 6) benefits and future work with the laboratory-scale system. Some of the concepts that are presented in this paper have yet to be implemented during 2018.

***Keywords**:* Drilling Automation, ROP Optimization, Modeling, Fault Detection, Drill String Dynamics

1. INTRODUCTION

While drilling automation in the past has been largely focused on implementing rig floor equipment that minimizes risk to rig floor personnel, drilling automation tomorrow is all about developing and exploiting the current state of art solutions that exist to the entire operation of drilling a well. To help accelerate the focus on drilling automation, highlight the ongoing digitalization effort in the industry, and allow students to carry out research, a 2nd generation laboratory-scale drilling rig was designed and constructed at the University of Stavanger in 2017. The 1st generation of the rig concept was developed at the International Research Institute of Stavanger (IRIS) [1] [2] in 2016. The drilling rig is designed according to identified research areas of interest at the university and a series of criteria defined by the Drilling Systems Automation Technical Section (DSATS) of the Society of Petroleum Engineers (SPE) [3]. These criteria have been met to allow the students involved in the project to annually participate in the international Drillbotics™ competition, in which an unknown rock sample of 0.6m height, must be drilled autonomously with the highest possible drilling efficiency, i.e. rate of penetration (ROP), without any human intervention.

Major benefits with the laboratory-scale drilling rig are that its key systems are fully interchangeable (which allows for continuous development and testing), relatively inexpensive components and sensors, minimized risk to personnel and the system, full-time access to the system and more importantly immediate results when testing prototypes, implementing models, algorithms and so on. As the system is required to fully penetrate an unknown rock sample without human intervention, it must be capable of accurate detection and handling of drilling incidents that could damage the system and prevent further drilling. The rig allows the team to design unique experiments to thoroughly investigate drilling incidents and attempt to identify the best remedial actions. Although some differences exist between a full-scale drilling operation and drilling in a laboratory at surface conditions, research with the system is expected to further strengthen the understanding of common causes of drilling incidents such as for instance stuck pipe or damaging bit vibrations. It is also expected that the system will be helpful to develop more accurate models that can be related to real-life drilling phenomena.

2. RIG OPERATING PRINCIPLES

The laboratory-scale drilling rig is designed to imitate the main functionality of a normal offshore drilling rig. Both consist of several key systems such as rotation/power transmission to the bit, a hoisting system for tripping in and out of the well, and mud circulation to remove cuttings and lubricate the bit and wellbore. There is however, one particular challenge when downscaling the full machinery to the laboratory scale. On the full scale, the combined weight of the assembly (bit, BHA, drill collars and pipes) is sufficient to provide the necessary weight on bit (WOB) to penetrate the rock formation. The neutral point is kept in the weight pipe / collars, and the actual drill pipe remains in tension which significantly reduces the risk of buckling and twisting off the pipe. On the laboratory scale, the weight of the pipe, BHA and bit is insufficient to provide such required WOB [1]. Thus, an additional force to just gravity must be exerted towards the formation, which on the laboratory-scale system is solved by using three linear actuators rather than traditional drawworks. Since adding WOB from above the drill pipe leaves the entire system in compression during the drilling operation, high caution must be taken with regards to the drill pipe which is the weakest component of the system.

Another challenge with replicating an actual drilling rig is the length of the total drill string assembly. To reproduce the slenderness of several kilometers of drill pipes, aluminum pipes with a low wall thickness (WT) can be used [2]. For this purpose, an aluminum drill pipe of 914.4mm length, an outer diameter (OD) of 9.525mm and a WT of 0.889mm is installed during normal drilling operations with the rig (such an aluminum pipe is also required in the Drillbotics™ competition).

To enable full transparency of the drilling operation, the designed system is unconfined, hence for all drilling operations surface conditions apply. This implies that one may assimilate the confined compressive strength (CCS) with the unconfined compressive strength (UCS) for the rock samples that are drilled with the rig [1].

3. RIG DESIGN AND COMPONENTS

3.1 Key Systems (rotation, hoisting, and circulation)

A brushless hollow-shaft motor is used in the rotation system. The currently installed top drive transfers torque directly to the drill string and provides a rated torque of 2.86Nm and a maximum instantaneous torque of 8.59Nm. The hollow shaft allows the mud injection hose to travel up the derrick and to be connected to the top drive from above, using a swivel (rotary union). Hence, the drilling fluid can be circulated through the rotating shaft of the motor and into the pipe at any time. The decision to attach the mud injection hose from above the top drive, rather than beneath, was made due to difficulties in locating small-scale rotary unions that wouldn't produce considerable amounts of viscous friction when the motor rotates at a high rotational speed in a low-pressure surface-environment.

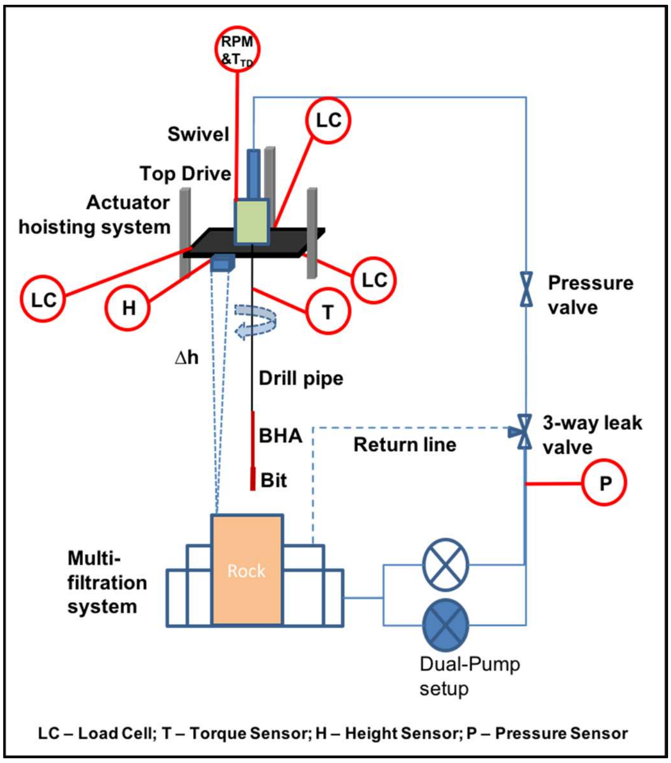

Fig. 1. Schematic of key systems and sensors in the existing solution. The combined weight of the derrick floor (hoisting plate) with all systems and sensors installed is approximately 200 N, depending on which bit, BHA and pipe gets used [5].

The top drive provides rotational speeds up to 3500 RPM. The RPM is however currently limited to 1500 RPM due to the rotary union which is being used. The RPM- and torque-output from the motor can be controlled by varying two analog voltage signals that get transmitted from programmable logic controllers (PLCs) to the dedicated motor driver which is used to control the top drive [4].

In the motor driver, a dynamic braking function exists. This function allows the autonomous control algorithm or the drilling engineer to define absolute motor torque limitations, in which rotation is immediately stopped if this limit gets exceeded. This suggests that for instance when drilling is conducted using fragile aluminum pipes that are very susceptible to buckling and twist-off due to their low mechanical strength and buckling limit, the maximum torque that the top drive can deliver can simply be programmed below the drill string yield point. The programmable braking function can be deactivated during experiments, for instance when simulating drilling incidents for research [4].

Three linear actuators that get operated in synchrony ensure a vertical well-path, and precise WOB. Each actuator is controlled by a dedicated stepper motor with a step-angle of 1.8 degrees, in which each step-angle consists of 10 micro-steps, i.e. 2000 steps/rev. Each lead-screw revolution corresponds to 8mm travel length, i.e. the system operates with an elevation resolution of 4µm. Very high actuator precision is required for optimal WOB control, which has been a key design criterion upon constructing the system. Since the actuator speed and travel direction constantly change during continuous drilling operations that last for several hours, and the holding torque in each stepper motor driven actuator is only 1.9Nm, the risk of overheating the stepper motors is greatly reduced with three such actuators in place. The stepper motors are also less likely to miss steps due to overload. As an additional precaution, normally-closed brakes have been installed on each actuator. These brakes only open when the system is in a drilling state [4].

The third key system on the rig is the mud circulation system. This system consists of two steady-flow membrane pumps, a pressure transmitter, two valves to simulate leak or overpressure, a rotary union and a filtration system that filters out cuttings from the drilling fluid before the mud is returned to the mud pit from which it gets re-used. The main objective of the circulation system is to ensure sufficient cuttings transportation out of the well, and lubrication of the drill bit and the wellbore. The pumps provide a velocity margin above the estimated minimum required 0.5 to 0.7 m/s range, and an average flow rate of approximately 11 liters per minute (LPM). With the current configuration, both water- and oil-based drilling fluids can be used, and the pumps can either be run separately or in parallel using solid-state relays [4].

To ensure equal terms of competition, the drill pipe and poly diamond crystalline (PDC) bit being used on the rig is provided from SPE [3]. Their specifications are in accordance with Table 1. Please note that a drill pipe with a 0.035” wall thickness is considered, since this is the dimension that was required to be used in 2017. Both the bit, BHA and drill pipes are interchangeable depending on the research being performed on the drilling rig.

Table 1. Drill pipe, BHA and bit specifications

Parameter	Description
Drill Pipe dimension	3/8” (OD) x 32” (L) x .035” (WT)
Drill Pipe material	6061 T6” - Aluminum
BHA dimension	14.9” length, 3 stabilizers
BHA material	SS316L - Stainless Steel
Bit dimension	1.125” OD, 2.35mm nozzle ID
Bit properties	Brazed cutters, 2 nozzles
Bit material	PDC-213

The BHA attached to the drill pipe is illustrated in Fig. 2. As is depicted in the figure, the bottom stabilizer is about to enter the riser guidance that will ensure that a vertical well path is drilled and limit lateral vibrations in the drill string assembly. Although the riser guidance is supported by a mount, competition regulations require that no support is added to the actual drill pipe, as this would make it very easy to eliminate lateral- and torsional vibrations [3].

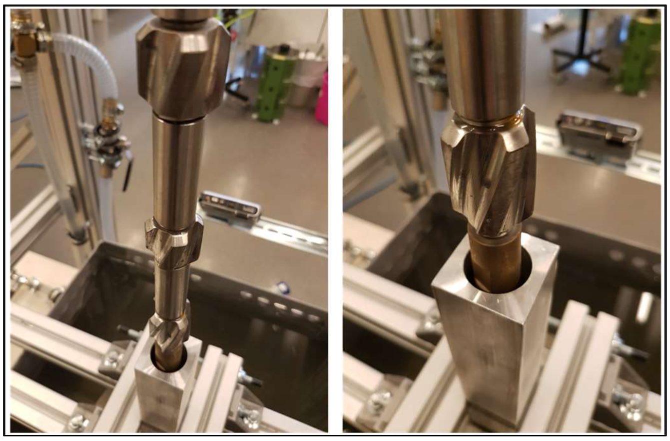

Fig. 2. Illustration of the BHA entering the riser guidance. A fully packed BHA is used to prevent well-path deviation.

3.2 Sensor Implementation

Autonomous systems rely on multiple sensors to determine and optimize the performance in real-time, as well as detect issues that could lead to drilling incidents. A total of 14 sensors have been implemented in the system, while several more will get implemented during 2018. The currently installed sensors are a torque- and RPM encoder in the top drive, a ferromagnetic torque sensor that can be attached at various positions along the drill string assembly to monitor torque, nine strain gauges distributed into three multi-axis load cells, a pressure transmitter, and a height sensor for bit elevation reference. Various switches and relays have also been implemented. All the sensors use a common analog communication protocol to the three Arduino Due microcontrollers (referred to as PLCs), all of which gather measurement data and carry out local tasks to their respective system. The sampling rate of each sensor is determined by the PLC loop time that the sensor transmits data to [4].

The aluminum drill pipe is the weakest component in the system. For this purpose, the torque sensors have been given the highest priority in the system. The top drive-torque encoder measures the combined torque of the power transmission assembly, i.e. bit torque, as well as the counter-torque (friction) that occurs in the top drive and the rotary union. To obtain just the bit torque, a correction factor must be applied. This correction factor has been obtained by measuring the motor torque at various RPM’s using the encoder, without the drill-string attached, to establish a baseline to calculate the bit torque at various rotational speeds. During real-time drilling, bit torque is calculated from the encoder using Eq. 1 [6]:

$$\tau_{bit} = \tau_{motor} - ((0.0015 * RPM) + 0.07175) \quad (1)$$

RPM is measured using the same encoder in the top drive that measures motor torque.

The second most important set of sensors are the multi-axis load cells that allow the system to measure the real-time hook load, WOB, and acting axial- and lateral forces. These can be either unwanted vibrations on the rig floor, or drill string- and bit vibrations that could damage the system and drilling operation, and therefore must be minimized. Each load cell is capable of measuring forces from -100N (tension) to 100N (compression) in all three load directions (X/Y/Z) and each load cell is mounted between the actuators and the derrick floor. To enhance the signal strength and tune the neutral point of the strain gauges, nine bi-directional amplifiers have been developed and implemented [4].

While absolute encoders could be installed on each stepper motor that drives the actuators, this would add an additional three sensors, and prolong the loop time for the PLC that is responsible for the hoisting system. Instead, the actuator positions are calculated using a digital step-counter algorithm. For instance, if the actuators need to move 5mm, this would correspond to 1250 steps, as one stepper-motor revolution (8mm actuator movement) corresponds to 2000 steps. Using the digital step-counter, the hoisting PLC can order the actuator to move in the appropriate direction until the desired number of steps have been counted executed in the PLC. As an additional method of verifying that the step-counting is accurate, an infrared height sensor is used as a height adjustment reference. A laser sensor will be installed in 2018 to increase the accuracy. To reset the position trackers (step-counting and height sensor), pushbuttons are installed on each of the actuators. The system is unable to drill until all pushbuttons are pressed during the calibration procedure. To protect the strain gauges in the load cells from overload, e.g. if a stepper motor overheats or malfunctions, or data communication is lost, several algorithms (PLC-localized) prevent asynchronous or unsupervised movement of actuators [4] [6].

Finally, a pressure transmitter has been implemented at the pump discharge. The pressure sensor monitors the pressure in the system and is also used to calculate the flow rate Q. If repeated pressure readings outside of the accepted threshold are detected, a relay stops mud circulation, indicating leak or overpressure. All data from the sensors on the drilling rig are filtered using various digital filters, such as median-, moving average- and low pass filters (LPF), to improve the data quality that is received into the control system [4].

4. COMPONENT- AND SYSTEM REQUIREMENTS

4.1 Mechanical and Physical Limitations

As stated in Section 2, the weakest component of the system is the aluminum drill pipe used during normal drilling operations. Although the drill pipes are of a 6061 T6" aluminum alloy material, we assume pure aluminum to account for material deficiencies. According to "Sheasby et. Al. 2001", aluminum in its purest form has an ultimate tensile strength (UTS) of 89 MPa and a yield strength (YS) of 34 MPa. With a drill pipe of 914.4mm length, OD of 9.525mm and 0.889mm WT, the maximum torque that can be applied before the pipe shears is roughly 3.14 Nm. Using the same drill pipe dimensions, the maximum torque that can be applied before the pipe yields is 1.873 Nm [4] [6]. This corresponds well to the torque limits estimated by Cayeux et. Al. 2017 for expected torques at different WOB on laboratory-scale systems [1].

Experiencing a twist-off is however not the only risk to the drilling operation. If a too high WOB is applied, particularly when combined with high rotational speeds, a significant risk of pipe buckling exists. Therefore, we must calculate the maximum allowable WOB, corresponding to the critical buckling force (CBF) of the pipes. Assuming a non-rotating static pipe with aforementioned dimensions, the CBF is [4] [6]:

$$CBF = \frac{(\pi^2 * E_y * J_z)}{(kL)^2} = 218.1\ N\ pinned\ or\ 26.7\ N\ swaying$$

By assuming that the CBF is even lower when the drill pipe is rotating, WOB must be kept well below 218.1 N during drilling to avoid buckling. This WOB limitation is within the load cell constraints before the axial strain gauges become damaged. The maximum allowable overpull must also be calculated, as the system will attempt to lift the bit off the formation if for instance a stuck pipe scenario occurs. The maximum overpull the pipe can endure is roughly 1129 N. Even if the three stepper motors that drive the actuators could produce such a lifting force, the maximum overpull and WOB the load cell strain gauges can sustain is currently 103,8N. Hence, in the axial direction, WOB must never exceed 218.1N (compression) and never go below -103.8N (tension) [4].

For all system boundaries that have been hardcoded in the system with regards to the drill pipe mechanical strength, a safety factor (SF) of 1.1 is applied [7], accounting for material deficiencies, system latency and so on.

4.2 Data Quality and Response Times

In the current installation, three Arduino Due PLC´s are being used as real-time decision controllers (RDC), one for each key-system. The Arduino Due is a 32-bit ARM core micro-controller with 54 digital input/output pins, 12 analog input pins and digital-to-analog conversion (DAC) capability. These PLC´s can be used to power sensors or control the different systems, by outputting either a dynamic 0 to 3.3V signal or continuously outputting 5V directly from the board. Since each board only has a 84 MHz clock and a limited flash memory, all data that are needed for time-consuming calculation of complex models and visualization in the human-machine interface (HMI) is communicated to a computer [4].

To ensure that the system can operate satisfactory, the data quality must be of a persistently high quality. The response times and sampling frequencies must also be high enough so that any potential incident can be detected and handled before the system becomes damaged. If for instance a rock sample is being drilled at 500 RPM using an aluminum pipe with 0.4064mm wall thickness (0.016"), and the bit very suddenly comes to a complete stop, rotation in the top drive must be stopped in less than 33ms to avoid twist-off [2]. Both detecting the stuck pipe scenario in the control system, programming the top drive to stop, and brake the motor until it comes to a complete stop needs to happen in less than the blink of an eye. Due to such requirements to response times, the control system is built according to a principle of performing all time-critical, deterministic operations directly in the Arduino Due PLC´s. By doing so, incidents such as drill pipe twist-off, buckling, overpull, leak, overpressure and so on, can be detected and handled consistently in the least amount of time without risking jeopardizing the entire drilling operation due to latency [4].

In the existing system, there have been several issues with the data quality and reliability of data received. These are largely caused by electromagnetic interference (EMI) from the 3-phase-powered top drive, inconsistent sampling frequencies between the three different PLC´s and invalid data, either due to the inconsistent sampling frequencies or sorting of incoming data in the code. Several solutions are currently being worked on to improve the data quality in the future [8]. To handle the signal noise, Fast Fourier Transformation (FFT) is being used to identify which frequencies in the signal that result from noise, and which represent the actual measurements. A series of digital filters are currently being developed and implemented to solve this challenge. With regards to the inconsistent sampling frequencies of the PLC´s, a solution has been identified in which all three PLC´s, which currently only communicate with the main computer, will be interconnected.

5. CONTROL SYSTEM ARCHITECTURE

5.1 Hierarchical Control System Architecture

As shown in Fig. 3, the control system of the rig is based around a hierarchical two-layered structure, in which a main computer, referred to as a Strategic Decision Controller (SDC), tasks the PLC´s to carry out local tasks within their system in accordance with the pre-programmed drilling plan. To allow the system to operate with varying thresholds depending on how far in the drilling operation it is, and to reduce the PLC´s loop times, the PLC´s have been programmed as finite-state machines (FSM). The top layer control algorithm is non-deterministic and hence not time-critical to execute. Data analysis, visualization of rig performance, fault detection and planning and coordination between lower-layer localized tasks are all carried out at this level. The bottom layer consists of the three mentioned Arduino Due PLC´s that gather sensory information from the three systems and execute local deterministic tasks. For example, movement of the actuators using a proportional integral derivative (PID) controller and controlling the top drive rotational speed, depending on which formation is being drilled. A USB communication protocol is used between the PLC´s and the PC, while CAN is being used from the HBM Quantum X DAQ to the PLC´s.

The concept during a normal drilling operation is that the system utilizes a sweep-algorithm, initiated by the SDC (PC), to obtain the highest ROP by manipulating the drilling parameters such as rotational speed (RPM) and WOB within acceptable limits. ROP, mechanical specific energy (MSE) and UCS are continuously calculated for performance optimization and identification of which rock formation is being drilled. The most optimal ROP is obtained when the lowest MSE is achieved (however MSE must always be > 0). When a significant MSE variation is detected, this indicates that there has been a change in rock formation and hardness. This resets the rotational speed and WOB to pre-defined, more moderate parameters, and the system needs to re-evaluate the drilling parameters by performing the sweeping-procedure again until a desired ROP and MSE is obtained [4] [6].

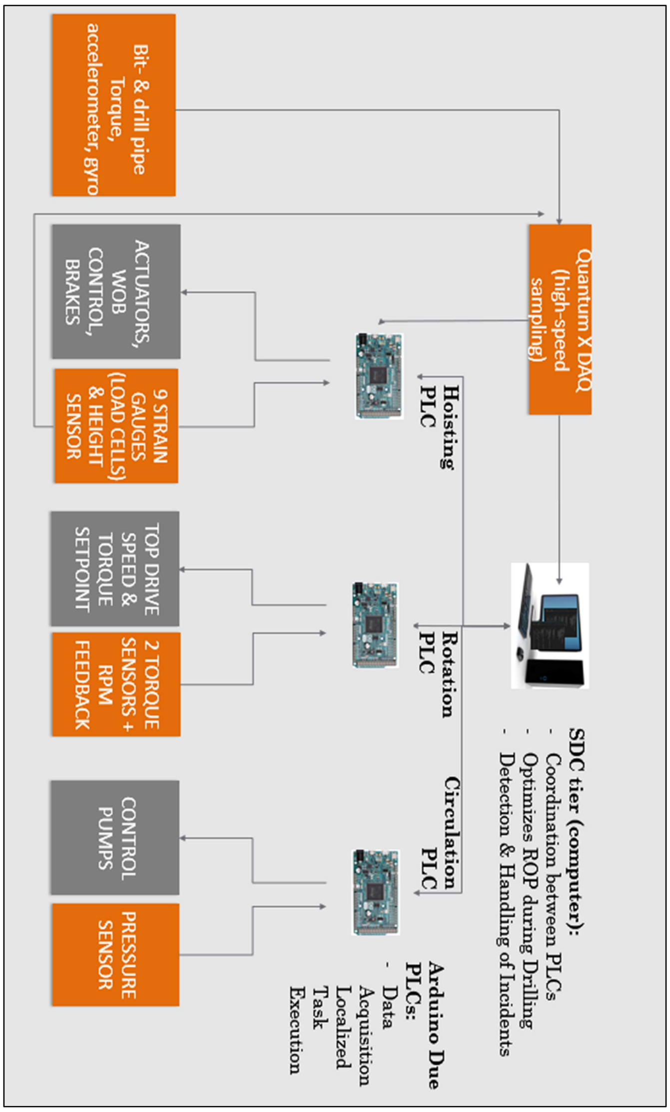

Fig. 3. Control system architecture, including the HBM Quantum X DAQ that has been added to provide high-speed data sampling to the PC.

5.2 Proportional Integral Derivative Controller

During normal drilling, WOB control of the small-scale rig is commenced with a PID controller (currently a PI controller, D-control is temporarily disabled due to EMI). The PID-controller is a multiple input single output (MISO) system, in which the error between the desired WOB of the system and the actual WOB, measured by the load cells, can be outputted as the distance (number of steps) that the actuators need to move in either direction to achieve the setpoint. A theoretical study of the suitability of using a PID controller for WOB control, combined with drill string dynamics modeling has been conducted to optimize the WOB control of the laboratory-scale rig. By eliminating challenges with noise (physical and digital filters), and adding D-control to the controller, the system is expected to run with a much higher WOB-precision. Research is also ongoing with regards to whether velocity control of the stepper motor delay function can be used instead of position control, or whether a torque PID-controller can be integrated with the WOB PID-controller (multiloop PID controllers), in which RPM is varied to achieve the highest torque-setpoint possible at the appropriate WOB-setpoint.

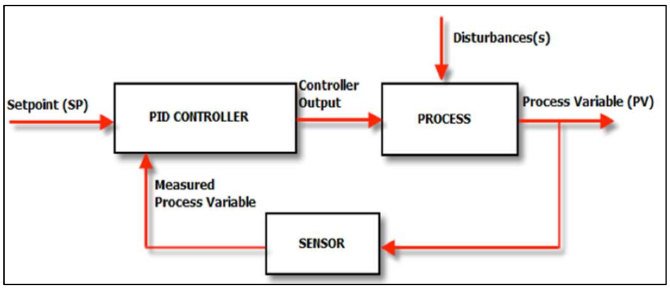

Fig. 4. Classic PID controller block diagram [9]. In the system, the setpoint is the desired WOB, determined in the strategic decision controller. The controller output designates the direction of actuator movement and number of steps.

5.3 Fault Detection and Handling Procedures

For the system to be perceived as fully autonomous, a pre-programmed drilling strategy is insufficient when the system needs to be capable of drilling unknown rock formations with varying hardness, formation dip etc., while simultaneously manipulating the drilling parameters to optimize the ROP in real-time and detecting and handling faults. For this purpose, a coordinator class has been implemented in the strategic decision controller algorithm. This algorithm class handles communication between the PLC´s, or it reacts if a deterioration in the drilling conditions is detected and enforces a pre-programmed remedial action to the specific problem that has been detected [6]. Currently, the system can identify and solve heavy axial- and lateral vibrations (that e.g. could lead to damaging whirl), significant torsional vibrations (referred to as stick-slipping), stuck pipe, overpull, leak and overpressure. Experiments have been developed to artificially simulate these incidents and to tune the algorithms that are used to handle incidents.

For the case of overpull, the handling-procedure is as described in [6]: “The hoisting PLC is constantly checking for an overpull situation, as it will not be able to move a step if any of the load cells exceed the overpull threshold. If the threshold is exceeded, the coordinator will be notified, and a command will be sent to overwrite the current command, to send the hoisting down 1mm. Immediately after the hoisting is lowered 1 mm, the coordinator will overwrite the top drive RPM to an initial value of 300 RPM in the case of no beginning RPM. The hoisting will then be raised at the slowest allowable speed set by the stepper motor limitations to try to ream the hole open. During competition drilling however, since the only two scenarios where the bit needs to be raised are during calibration and stick slip mitigation, there is no need to ream the hole. As such, if overpull is encountered, reaming can be dismissed, and the upper hoisting position limit can be reset to the current position”.

6. DEVELOPMENT OF MODELS AND RESEARCH

6.1 Rate of Penetration Model

Several equations and models exist to calculate the ROP of a drilling system. They do however, all require the rock hardness or the so-called d-exponent (rock drillability) to be known. Considering this, they all become very inaccurate if an unknown rock sample is drilled, because one simply would have to assume a value for the rock strength. Seeing that a paramount objective when the autonomous drilling system operates is that it continuously attempts to optimize the ROP, two methods (both time-based as opposed to depth-based) are currently used on the rig to calculate the ROP as a change in bit elevation over a set time interval [4]:

The first method considers that a rapid change in the ROP must indicate a change in the drilling conditions. This rapid change in conditions could, if not handled appropriately, lead to a drilling incident such as stuck pipe (if for instance a homogenous soft rock has been drilled with a very high WOB for maximum ROP-gain, and a significantly harder rock that should instead be drilled with a low WOB and high RPM has been encountered). This method is referred to as instantaneous ROP calculation and considers the change in bit elevation over the last 15 seconds. The instantaneous ROP is updated every second, by collecting 15 measurements of the bit elevation (one measurement per second), and every second replace the obsolete data with a new measurement [4].

The second method is used for ROP optimization and is identical to the first method with the only exception being that the time interval is now extended to 180 seconds. This is referred to as the overall ROP. To understand whether the ROP of the system is ideal, or whether the rotational speed or WOB parameters must be adjusted, the overall ROP is used by the autonomous control algorithm to assess whether adjustments have the desired effect and to visualize rig effectiveness [4].

The use of MSE to assess the drilling efficiency became a standard for surveillance of rig data after Dupriest, Koederlitz and Weis began to compute MSE during drilling on full-scale rigs [10]. Based on this, the system calculates the MSE from Eq. 2 [11]:

$$MSE = \frac{4\,\tau_{bit}\,RPM}{\pi\, d_{bit}^2\,\mathrm{ROP}} + \frac{4\,WOB}{\pi\, d_{bit}^2} \tag{2}$$

Whenever a drilling parameter (RPM or WOB) has been changed, the system assesses the new MSE and ROP, before any adjustment is made. The ROP is attempted optimized as much as possible, until drilling incidents, or a strong indication of a change in rock formation hardness, gets detected and the parameters are lowered. The optimal point should be when the MSE is low (i.e. the least amount of excess energy is wasted to remove the rock volume) and the ROP has increased up to a point in which the system experiences a near non-linear state, without reaching the so-called Founder Point. At the Founder Point, the drilling conditions have become suboptimal and the bit, BHA or other components could become damaged [4].

According to Cayeux et. Al. 2017 [1]: “To find an optimum working point, the WOB is increased linearly for a small variation and the response of the ROP to the change is analyzed". Then, RPM is increased linearly and ROP response analyzed. Thus, if a linear response is seen, WOB can be increased. If the response is non-linear, then WOB must be decreased. A transition from a linear- to a non-linear response indicates where the Founder point is (when response becomes non-linear). Similarly, the process can be repeated with RPM instead of WOB, and a cube algorithm can be used for ROP optimization. For more details, see [1].

6.2 Formation Change Detection

A change in rock formation can be detected by the system if:

• A gradual increase/decrease in overall ROP is observed or the instantaneous ROP increases/decreases rapidly and remains outside of threshold (formation change or incident),

• Large variations in the calculated models that indicate effectiveness or hardness such as MSE and UCS occur.

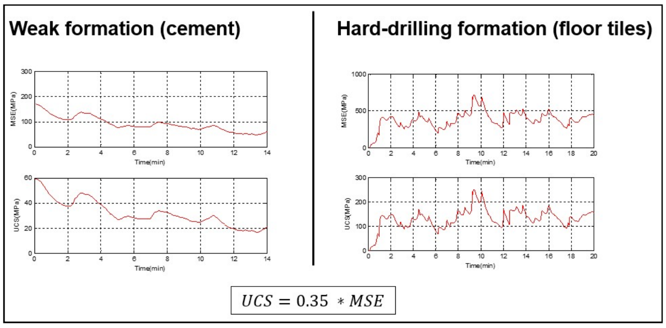

Fig. 5. Drilling experiment in which cement and floor tiles were drilled to investigate whether MSE and UCS can be used to distinguish between rock formations on laboratory scale.

Fig. 5 presents some results from an experiment, in which two rock samples with varying formation hardness were drilled. The MSE and UCS were then calculated following the experiment, based on the gathered data. Even with significant EMI-noise present in the dataset, a clear distinction in MSE and UCS can be observed. This indicates that the system highly likely should be capable of distinguishing between different formations with varying hardness by calculating the average UCS over a set time interval. A future priority is to drill a wide variety of rock samples and create a database in which observed MSE, ROP, UCS and so on, can be associated with the respective rock samples drilled by the system.

6.3 Drill String Vibration Model

Drill string vibrations is a complex phenomenon, which frequently results in nonproductive time. The complexity lies in the coupled action of the three vibrational modes: axial, lateral and torsional. The modes excite one another, which makes it difficult to recognize a particular mode and prevent or mitigate their further destructive effect. Therefore, this topic has been identified as a key research area of the theoretical study performed using the set-up described above. The ongoing work is aimed to develop a downhole tool to measure bit-acceleration, bit-torque and inclination during drilling and store this data for later analysis. This will be done with the primary objective to determine the following:

• The natural frequency of the system under various loads and rotational speeds,

• The dominant mode of vibrations for particular operational conditions,

• The magnitude of forces the BHA and the bit are exposed to during drilling,

• System respond to initial conditions and no-load, i.e. external forces are equal zero,

• The system's transient response to external loads.

Analysis of the drill string dynamics (for ex. vibrations) can be studied through mass-spring-damper models. A drill string, constrained between the rotary table and the well bottom, can be discretized into segments, which represent mass elements of a beam. Their response to the external excitation, either constant or periodical, can be described by a second order ordinary differential equation (ODE), which is known as the equation of motion:

$$[M]\{\ddot{h}\} + [b]\{\dot{h}\} + [k]\{h\} = \{F\} \tag{3}$$

The first term in Eq. 3 represents Newton's second law, the third one Hooke's law and the middle term relates viscous damping to the velocity of the system. The term on the right-hand side represents external forces acting on the system. Squared brackets are used for M (mass), b (damping) and k (stiffness) matrices for each element, with size nxn, where n is the number of degrees-of-freedom of the system (DOF). Curly brackets are used for vector matrices: displacement, velocity, acceleration and external forces. These are the functions of time and their size is nx1. The abovementioned equation of motion with no damping present can be derived from the Lagrange's equation:

$$\frac{d}{dt}\left\{\frac{\partial T}{\partial \dot{h}}\right\} - \left\{\frac{\partial T}{\partial h}\right\} + \left\{\frac{\partial V}{\partial h}\right\} = \{F\} \tag{4}$$

T is a kinetic energy of the system and V is potential energy of the system. For the detailed derivation, please see [12].

Depending on the objective of the study, the model can get various levels of complexity. Axial vibrations can be studied by assuming a single degree-of-freedom (SDOF) system. The model can be extended stepwise to twelve DOF for each element (three displacements and three rotations for each node; each element has two nodes) to study the complete system. For the current drill rig design, the most practical would be to study the axial and torsional vibrations, as the BHA is constrained by the riser and the wellbore walls, thus the annular clearance is very small.

A downhole measurement system is a useful tool, which will allow the team to capture the moment when vibrations occur and adjust operational parameters (WOB and RPM) in real-time to mitigate the damage to the string components. The ultimate objective of this theoretical study is to be able to control the operational parameters to reduce the destructive vibrations real-time and suggest universal recommendations how to prevent occurrence of vibrations.

7. RESULTS, BENEFITS WITH THE LAB-SCALE SYSTEM AND FUTURE WORK

7.1 Experimental Drilling Results

An experiment was conducted to investigate what effect just increasing the RPM would have on the ROP, if the WOB setpoint was fixed at 19,6N (2kg). Different speeds were maintained during the operation, to allow for drilling of a pilot hole at moderate performance, and to collect data on the vibrations that occur at those speeds (extensive vibrations and whirl has typically occurred in the past). From the data, it was observed that the instantaneous ROP peaked at approx. 12 mm/min (0.72 m/hr). The overall ROP, which is an average of the last three minutes of drilling peaked at around 9.5 mm/min, because the system was only allowed to drill a limited time at maximum speed. From similar experiments of drilling homogenous cement, where the rotational speed was kept at 700 RPM, and WOB was increased to a 49N (5kg) setpoint, ROPs of approximately 16 mm/min (0.96 m/hr) were obtained. At this combination however, some occurrences of whirl were detected, indicating suboptimal parameters with an increased risk of damaging the bit and other vital components [4].

7.2 Benefits and Future Work

Projects that involve designing and constructing laboratory-scale systems are beneficial to understand, evaluate and investigate the state of the art technologies and solutions available in the industry. This addresses a wide range of challenges such as equipment and control system design, information/machine/human integration, data quality control, development of models (rate of penetration model, drill string dynamics, etc.), performance optimization and so on. Future work with the designed and constructed laboratory-scale rig at the University of Stavanger include the following upgrades:

• Improved system-wide communication protocols & improved data quality through implementing digital filters (e.g. Kalman filtering) and interpolation resampling methods,

• Mechanical upgrades of several key components such as pipe connections, riser guidance and riser mounting,

• Develop prototype downhole tool and fully implement ferromagnetic torque sensor and strain gauge rosettes for near-bit measurements and drill string dynamics- and vibrations research,

• Investigate advantages and opportunities with integrating machine learning algorithms to the control system, hereunder machine learning rock classification and formation evaluation algorithms,

• Improved HMI to better visualize the drilling operation and better allow the drilling engineer to take manual control of the system and develop a remote plug-and-play concept.

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