UND PETROLEUM ENGINEERING
UNIVERSITY OF NORTH DAKOTA

UND Design Report- Drillbotics 2019

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Nomenclature

BHA	Bottom Hole Assembly
BUR	Buildup rate
MSE	Mechanical specific energy
RPM	Revolution per minute
TD	Total Depth
TVD	True vertical depth
UDE	Undesired event
WOB	Weight on bit

1. Introduction

Drilling objectives include drilling wells safely, economically and in environmentally friendly manner. Drilling automation can reduce risks that involve personnel as well as the risks resulting from man error. Some of these errors can lead to environmental and/or economic disasters. Yet, drilling automation is a very complex process due to the number of hyper parameters involved in drilling operation. The complexity of the process is in both design and implementation phases. Directional drilling has a wide range of applications such as offshore platform drilling, accessing reservoirs beneath salt domes, sidetracks, relief wells, drilling in inaccessible locations, developing unconventional reservoirs and others. Successful automation of directional drilling process can save millions of dollars by saving time and energy consumption, but it is more complex than that of vertical drilling. Drilling System Automation Technical Section (DSATS) realized the potential of investement in university students through Drillbotics competition not only can result in innovative solutions, but also make the future industry people accepting and familiar with automated drilling. This overcomes a main challenge that face the culture of automating the drilling process, the fact that human prefers what they already know and are experienced with.

This year's competition aims at autonomous directional drilling system. As previous years, dealing autonomously with drill sting mechanics is still a concern. The study of this concern is more complicated this year as the pipes would have to bend with the trajectory of the hole in addition to optimizing bottom hole assembly (BHA) configuration for directional drilling.

This report is the deliverable for phase I of 2018/2019 drillbotics competition. The report includes updates from last year's design to enhance the performance and propose a preliminary design for our directional drilling technique as well as summary for last year's design. The report also discusses drilling aspects that affects our design. Further, Safety concerns and mitigation actions will be detailed as well. Also, the mechanical aspects for the drilling rig system will be discussed. Additionally, the planned control system and instrumentation for the drilling process will be illustrated. Finally, budget and cost control strategy will be summarized.

2. Safety

Any process has its own risks and safety concerns. Oil and gas industry is one of the most hazardous industries with several undesired events occurrences each year that can lead to loss of human lives and/or millions of dollars. The drilling process and its surrounding services is on the top of the list regarding the accidents in the petroleum industry. The outcomes of these undesired events can affect assets, human and environment intensively. One of the main drives for drilling automation is to reduce the risks that involves human as a source or as an object. Our lab-scale drilling rig have different risk assessment than full field-scale rig. For example, having a blowout is almost of zero probability due to the absence of hydrocarbons in the rock sample. The risk assessment for the project including upgrading and testing phases is summarized below. A brief explanation of the concept of the risk matrix is presented first. Then, the summary of the rig risk assessment will be introduced.

The steps of risk management include identifying the system, identifying the possible hazards, estimating the different risks, evaluating these risks then controlling the risks. The system identification includes assets and equipment, personnel and environment. Identifying the hazards is through expecting the undesired events (UDE) of the different processes through different phases. In risk estimation, the probability (table 1) and severity (table 2) of these undesired events

Table 1: UDEs probability ranks legend

PROPABILITY	P1	P2	P3	p4
RANK	Unlikely	May Happen	Likely	Certain

Table 2: UDEs severity effects Legend

Severity	S1	S2	S3	S4
Effect	Minor	Significant	Critical	Catastrophic

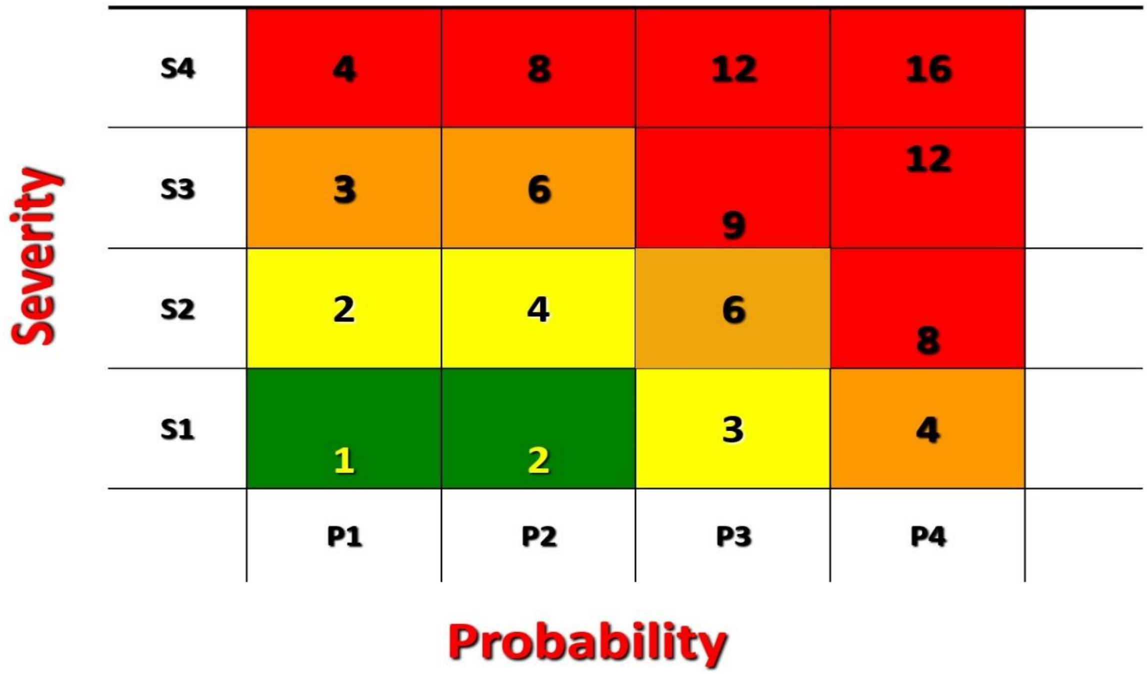

Figure 1: Risk matrix concept

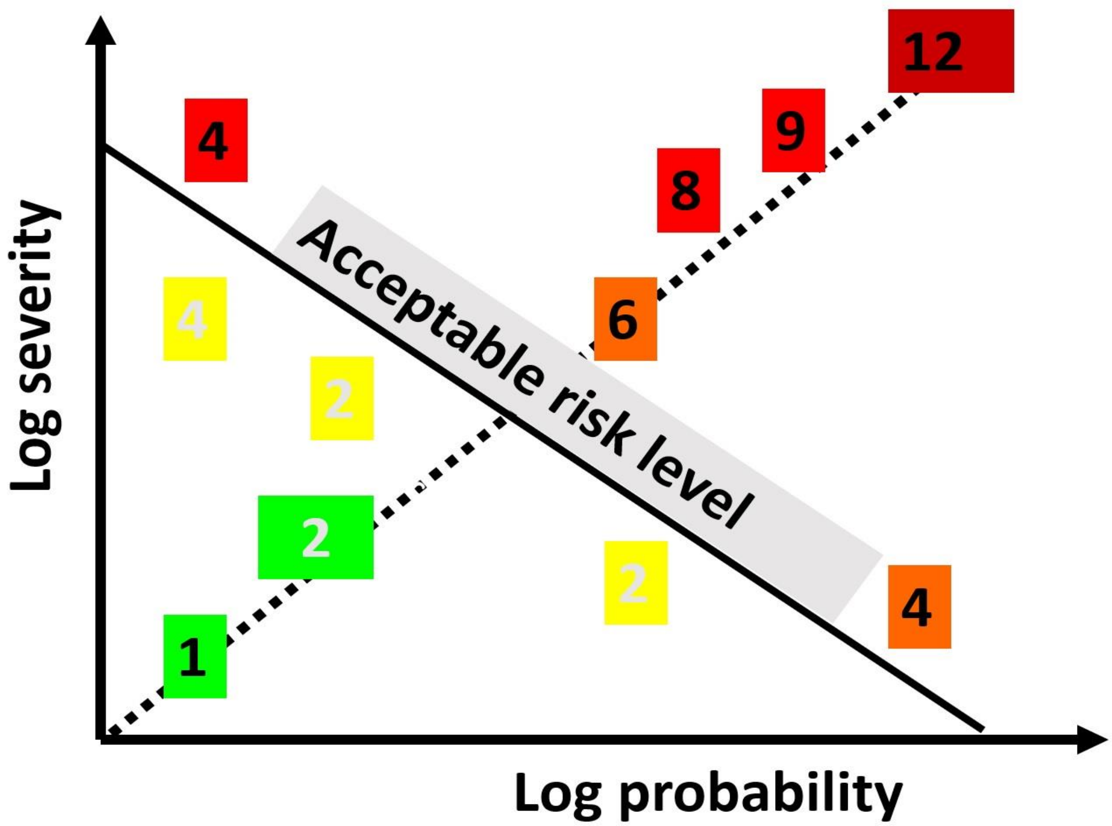

Figure 2: Risk Evaluation and accepted risk level

are estimated. Then, the different risks are quantified using risk matrix (figures 1 and 2). Finally, the proper mitigation and/or contingency action for each risk is decided. Table 3 shows a summary for the risk assessment of major risks involved during manufacturing and operating of the rig for our project for several processes.

Table 3: Assessment for examples of project’s major risks

Source	UDE	Probability	Severity	Risk Rank	Control
Heavy objects	Inappropriate lifting	3	2	6	-Safe lifting introduction -Mobility facilitating tools -PPE -First aid kit
	Fall	1	4	4	
Sharp edges	Personnel injury	3	2	6	-PPE -Covering sharp edges with elastic corners -First aid kit
Unsafe behaviors	Personnel injury	2	2	4	-Safety meetings -PPE
Bad insulated electric components	Electric shocks	2	1	2	-Good insulation -PPE -Circuit breakers -Emergency button
	Circuit failures	2	2	4	
Electronics	Failure	2	2	4	-Ensure appropriate cooling -Avoid excessive usage -Ensure use of appropriate components
Bit	Failure	1	3	3	-Bit cooling -appropriate drilling parameters selection
Drillstring	Failure	2	3	6	-proper design -testing
Debris	Personnel Injury	1	3	3	-PPE

					-Acrylic safety sheets
Mechanical parts	Failure	2	3	6	-Inspection -Maintenance

3. Directional Drilling

UND team have decided to use its own technology to simulate downhole motors for directional drilling. Plan A includes modifying an air die grinder as a downhole mud motor and car mirror adjusting motor as a controlled deflection tool. The vertical hole will be drilled using a top drive system. Then, the combination of downhole motors will be used to continuously build the inclination angle while maintaining the azimuth at minimum value (hopefully zero).

3.1. Mud Motor

The air die grinder (figure 3) will be used to rotate the bit in the sliding drilling mechanism. In fact, we won't just use a stock air grinder, several modifications will be applied to meet the required functions. These modifications include using water rather an air as a driving fluid, changing the inlet angle and the external housing.

Figure 3: Commercial air grinder

Using water rather than air as a driving drilling fluid would result in two main advantages; higher torque and better bit cooling. On the other hand, using water is expected to result in lower revolution per minute (rpm). Theoretically, the maximum rpm of the air die grinder can reach 20,000 when it is facing no resistance (free speed rpm). The max rpm in the case of drilling is expected to vary depending on the lithology of the drilled formation, drilling fluid used and bottom hole assembly (BHA). The applicability of using water with an air grinder is to be tested on phase II. In case it goes negative results, air or aerated mud can be used.

Changing the inlet angle and the external housing is essential to adapt with the well profile. The inlet makes an angle of 90° with the body of the air grinder. The plan is to change the angle to zero degrees. We will be testing the effect of having a minor angle as we expect it can help in building up the inclination. The external housing is to be replaced by home manufactured one with minimum dimensions to increase the flexibility of the BHA.

3.2. Deflection tool

Another big challenge for directional drilling on this scale was to find a deflection tool that allows auto-navigation. Among several ideas, a car mirror adjusting motor was selected as plan A to allow full steerability and due to its dimensions. The used motor will be modified to allow larger cross-sectional area for fluid flow. The fluid pressure is crucial as it act as a driving force for the mud motor that rotates the bit. Also, we might have to manufacture the motor's housing to reduce the dimensions. The force offered by motor is still questionable in presence of drilling forces. Drilling sandstone formation requires less force to build the angle compared to harder formations. Figure 4 shows an example for car mirror adjusting motor dimensions. The dimensions on the figure are in mm. Testing would show the maximum build up rate that can be attained by this deflection tool when used in combination with air grinder. Selecting a higher horsepower motor would subsequently increase the motor's dimensions. These types of motors are relatively cheap and available that you can get one of them from a junk yard. Plan B would be contacting one of the manufacturers to get a higher horsepower within a compact size in a special edition for our purpose, but this might significantly raise the cost.

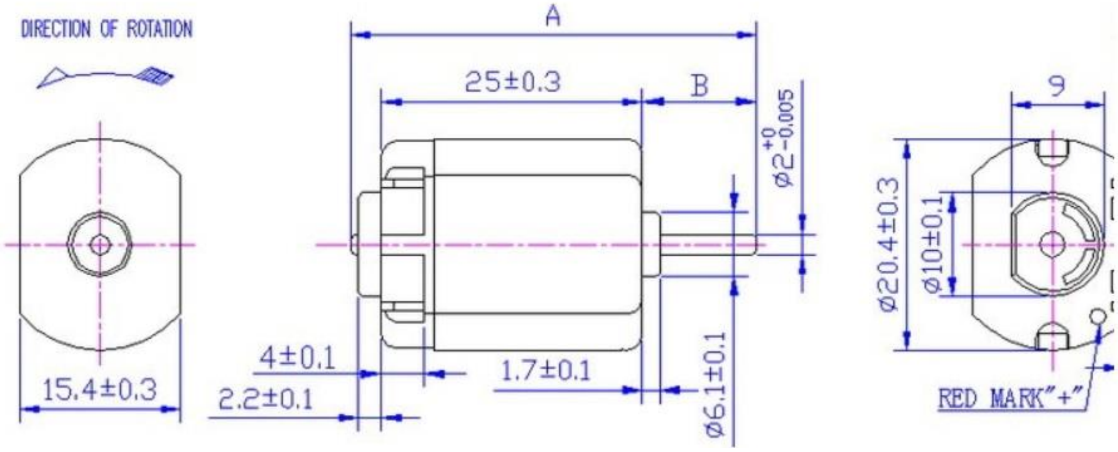

Figure 4: Dimensions of an example car mirror adjusting motor.

4. Engineering Considerations

This section presents miscellaneous engineering considerations including hydraulics, directional calculations, drillstring mechanics and others.

4.1. Hydraulics

When planning the drilling fluid calculations, the team decided to opt for the maximum available volume of water to ensure the borehole would be kept flushed of any heavy cuttings and the drill bit would be sufficiently cooled. Using clean tap water, the team modeled the dimensions of the borehole with a plastic tube of similar dimensions at TD and measured four gallons per minute to be that max volume that will keep the bore flushed without a 'blowout.'

The system pressure drop was calculated through the bit (smallest restriction in the system).

$$Pb = \frac{q^2 W}{12031\ A^2} = \frac{4*8.3}{12031*0.01094^2} = 23.040\ psi$$

Where:

q = flow rate in gpm,

A = nozzle area in square inches,

W = water weight in ppg.

The classroom example of also of a full-size model was calculated for pressure loss through the pipe

$$\frac{dpf}{dL} = \frac{8.3*(61)}{25.8*(0.277)} f = 70.84\, f \text{ psi}$$

Note: this model yields a result of back pressure approaching full system pressure even without the value of f.

This shows a VERY low resultant water pressure remaining. Model testing showed this was not accurate.

The team then chose to use a more scalable model, The Darcy-Weisbach and the Hazen-Williams equations typically used in plumbing systems. The H-W roughness factor, contributing to friction, for vinyl hose and aluminum pipe, as used in the drilling rig, are both 150 coincidentally.

$$S_{\text{psi per foot}} = \frac{P_d}{L} = \frac{4.52\, Q^{1.852}}{C^{1.852}\ d^{4.8704}}$$

Where:

Spsi per foot = frictional resistance (pressure drop per foot of pipe) in psig/ft

Pd = pressure drop over the length of pipe in psig

L = length of pipe in feet

Q = flow rate, gpm

C = pipe roughness coefficient

d = inside pipe diameter, in

This yields a psi drop of 8.37 psi through the pipe, a much more realistic value at this size and scale.

Bit hydraulic HP: $Hb\ =\ \frac{23040*4}{1714}\ =\ 0.053$ hp

Pressure drop through pipe and bit: 23 + 8.3 = 31.3 psi

This is not accounting for any pressure loss through the hose, which will be very similar to the pipe (per unit length) since they have the same friction factors.

Annular pressure losses:

$$P_a = \frac{1.4327 * 10^{-7} * MW * L * V^2}{D_h - D_p} \cong 0.013\, psi$$

Where:

P = annular pressure losses, psi

MW = mud weight in ppg

L = length of annular in ft

V = annular velocity in ft/min= $\frac{24.5\ Q}{D_h^2 - D_p^2}$

Dh = hole or casing ID in inch

Dp = drill pipe or drill collar OD in inch

The value show may sound very low compared to field scale values. This due to the flow rate and annulus cross-sectional area. This value doesn't count for any annular restrictions such as subs or stabilizers.

4.2. Directional Calculations

Initial guidelines specified the target point to be 4 inches above the bottom the sample bottom in the north directions (figure 5). The following calculations are based on these assumptions.

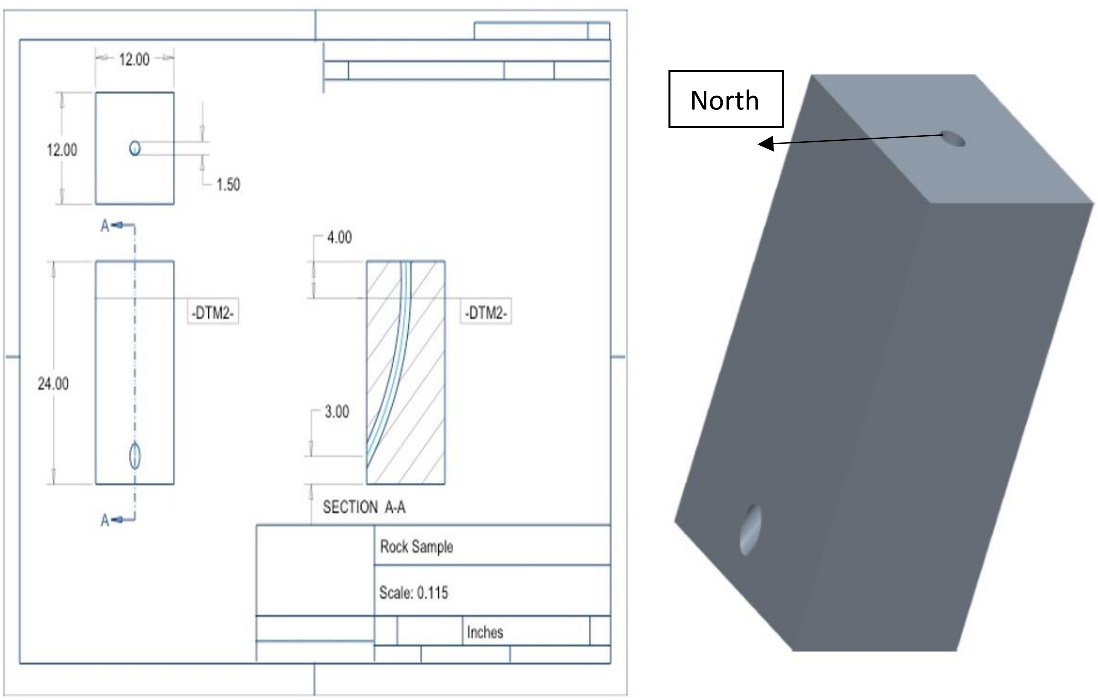

Figure 5: Initial guidelines propsed well path

$r sin\theta = 17$

$r(1 - cos\theta) = 6$

From solving these two equations $\theta = 38.88^o$.

Finding the value of radius

$r sin\theta$=17 , $\theta = 38.88$

r = 27.08 in.

Finding the Buildup rate (BUR)

BUR= 180/ $(\pi r) = 180/(\pi * 27.08)$=2.115°/in

The Calculations can be summarized that the maximum inclination angle $(\theta) = 38.88^o$, the radius of curvature (r)= 27.08 inches and the BUR=2.115°/in in a continuous build profile.

This build up rate seemed to be impossible to achieve. The current status is to get as high BUR as possible. The target location would be limited by the maximum bend angle that can be obtained from pipe/BHA combination as well as the maximum bending angle for the pipe before failure (mechanical limit).

4.3. Drillstring Mechanics

This section includes the mechanical limits for the drillstring which is based on the previous year's calculations. Using a Euler's buckling model, the critical load of the drill string was found to be about 25N. The selected model was a fixed-pinned system, the connection to the drilling rig is considered a fixed connection and the connection to the rock is considered a pinned reaction since the force of friction while drilling would help keep the system in a single location. A fixed-free end system was also modeled with a critical load being about 20N. Both analytical models were verified by utilizing finite element buckling analysis, which yielded similar results. When adding lateral support close to the critical mode deformation location of as possible, finite element buckling analysis was conducted and results showed max critical load of 700N with a 1.5 safety factor from unknown effects of tool joints (figure 6). Further modification is needed for positioning the stabilizer for maximum building rate as well as changing the drill-sub length.

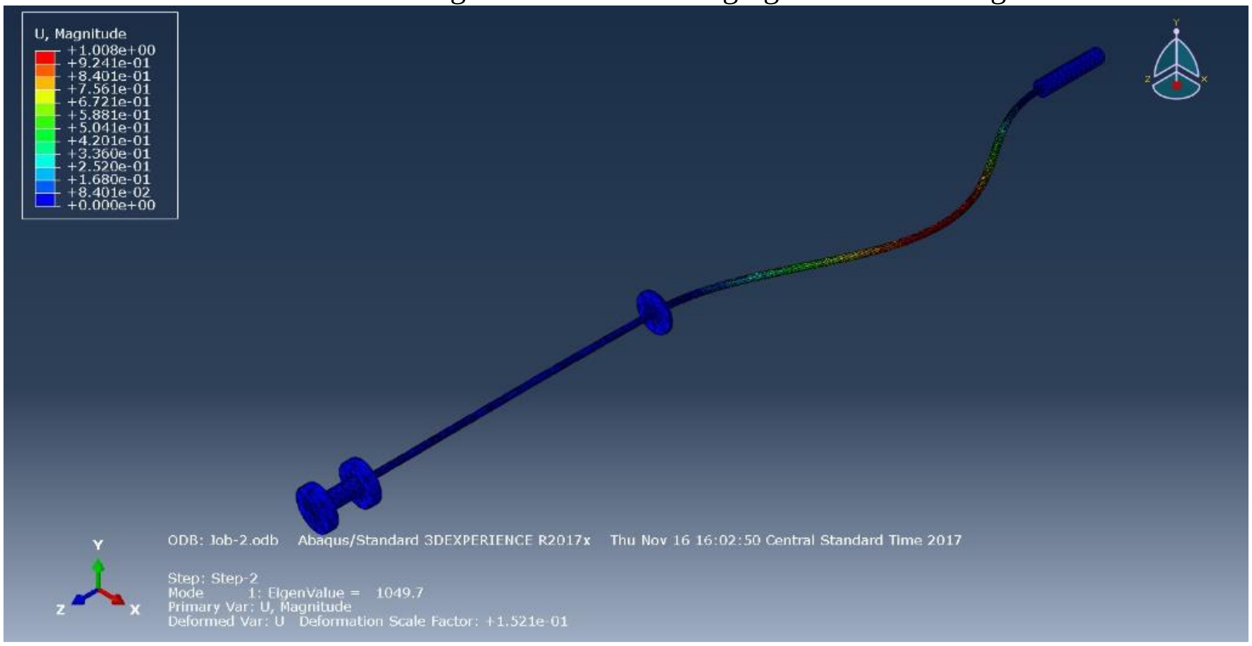

Figure 6: Finite element buckling analysis of drill string system.

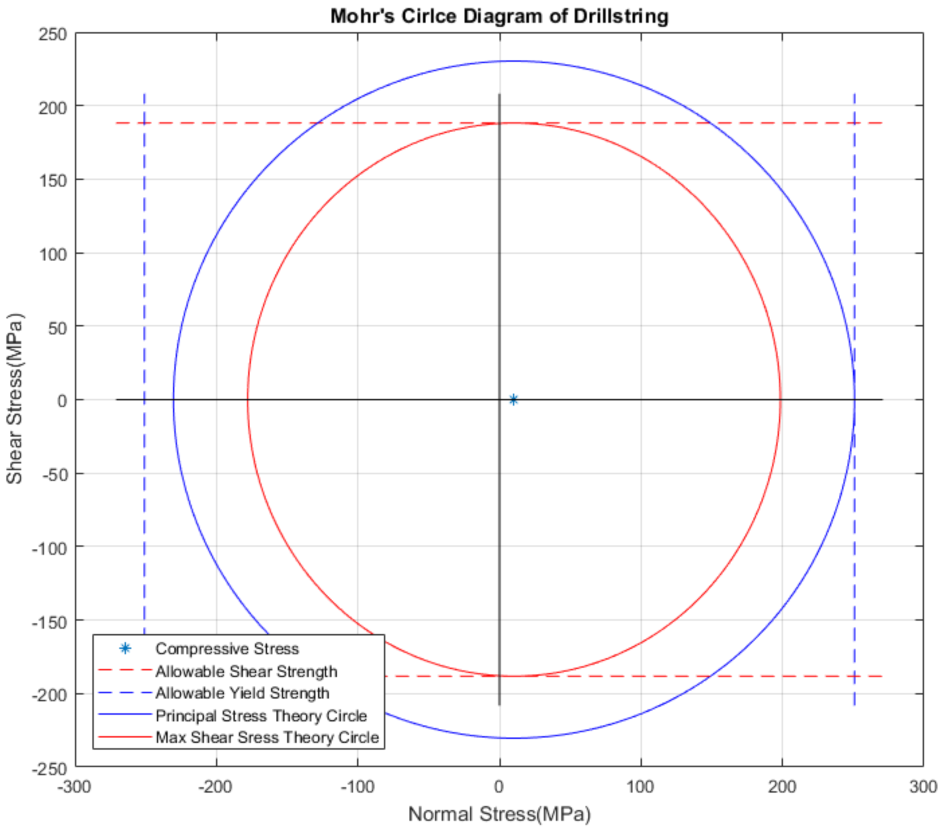

Figure 7: Drillstring' Mohr's circle for max principal stress and max shear.

To obtain a maximum allowable torque for the system, two failure methods were evaluated consisting of maximum principal stress theory as well as maximum shear theory. A Mohr's circle with both models (figure 7) shows that the drillstring would fail from maximum shear theory rather than maximum principal stress theory because the applied compressive stress is significantly low comparted to the material strength. Calculating the max allowable torque from the max allowable shear stress yields approximately 22Nm with a 1.75 safety factor due to unknown effects from tool joints.

The maximum bending angle for the drillpipes is limited by the material used. For used aluminum pipe, the maximum bending angle couldn't be found in references. It shouldn't be a limiting factor due to the flexibility of the pipe. Also, the rigidity of the BHA/pipe combination and the buildup rate expected make it a minor concern for the design.

4.4. Other Considerations:

Several other considerations are taken into account including true vertical depth (TVD) measurement, Weight on bit for directional drilling and measuring RPM when using downhole motor.

Measuring the true vertical depth for directional section of the hole is not as direct as the vertical portion. In the vertical portion, the displacement of the linear actuator is just measured. For the deviated section, the incremental change in linear actuator displacement measurement represent the change in measured depth (MD) not TVD. Survey calculations such as minimum curvature method will be used to obtain the downhole coordinates.

The weight on bit for the deviated section would have to be calibrated for the deviation angle as it is measured using a surface sensor. The following Equation represents actual weight on bit (WOB) for an inclination angle θ at the bit. Another proposed solution is using downhole sensor to calibrate WOB. Using downhole sensor would calibrate for both inclination and frictional forces.

$$WOB_{actual} = WOB_{available} * \cos\theta$$

In the deviated hole section, Slide drilling is pursued. In slide drilling, the portion of the drillstring at the top of the so-called mud motor is not rotating. That leads to zero RPM reading for the optical encoder installed at the top portion of the string. This makes it necessary to measure the RPM from the rotating portion of the string to get the downhole rpm.

5. Rig Upgrades

Several upgrades are planned from last year's rig. Some of these upgrades are related to directional drilling while others are related to operational problems. The operational problems from last years was mainly low rpm, low torque and control problems. For low torque and rpm, motor upgrade has been issued. This would help with the vertical section of the hole and then the downhole motor would drill the directional part in a sliding drilling mode. The following section summarizes the rig upgrades including motors, sensors as well as other upgrades. The control summary of the upgraded rig system is also included.

5.1. Top Drive Motor Selection/Upgrade

The main motor would be AC MOTOR, 1HP, 3450 RPM, 3PH/60HZ, 208-230/460VAC, 56C/TEFC, WITH FOOT, SF 1.15, this would be working with a VFD Controller.

The VFD controller would be Teco Variable Frequency Drive, 1 HP, 115 Volts 1 Phase Input, 230 Volts 3 Phase Output, L510-101-H1, VFD Inverter for AC motor control, PMW controlled, all these are Arduino controlled.

For the downhole motor, we would be using Pneumatic air grinder, this grinder would be modified to work with current design which include using water as driving fluid.

5.2. Stepper Motor System Selection/Upgrade

A motorized linear actuator, EAC Series Closed Loop Stepper Motor Linear Cylinders / Linear Actuators, this is a combination of linear actuator and motor, which helps regulate function. It also come with a controller.

5.3. Sensor Package

This year several down hole sensors are planned to be installed to enhance drilling performance and to control the directional drilling. Some of these sensors are mentioned below.

Accelerometer: IMU 10 DOF, 16g, 3 Axis Accelerometer, Gyro/magnetometer/Barometer

This is a combination of accelerometer, gyro, magnetometer and barometer. The barometer section would not be used, but the other sensors would be used. For more precision two of these would be used so we can cover 6 axes as each one can only cover 3 axes.

Temperature: Thermistors, 3950 NTC 10k Precision Epoxy, this works under drilling conditions and ideal for this project.

Linear position sensor: Potentiometric linear transducer MBX which is an extremely flat linear transducer ideal for tight space.

5.4. Hardware and Software Emergency Shutdown Button

The hardware safety would be a circuit breaker which would be attached to the DC source, that way in case of anything it can be switched off. The software safety would be embedded in the program coding. Arduino does come with couple of interrupt pins which would be used to setup an emergency shutdown function.

5.5. Electric safety upgrade

Since we are dealing with electric devices and drilling with water, every single wire has to be well covered and wiring would be done to keep electric devices away from the any water source. Also performing checks before and after each test to make sure we do not have any burned wires and other things that could go wrong.

5.6. System control

A general view would be a DC source into the VFD, which outputs 3 phase AC into the main motor that runs the drill. The sensors would be attached to the pipe downhole, and these sensors would be spread out into 3 different sections to allow bending downhole. The sensors would be embedded in a 3D printed frame and covered in epoxy to prevent damage. The sensor subs can be used as stabilizers. All these sensors would be connected and controlled by Arduino software, which would also have a display on LabVIEW. Figure 7 represents a schematic for the control system.

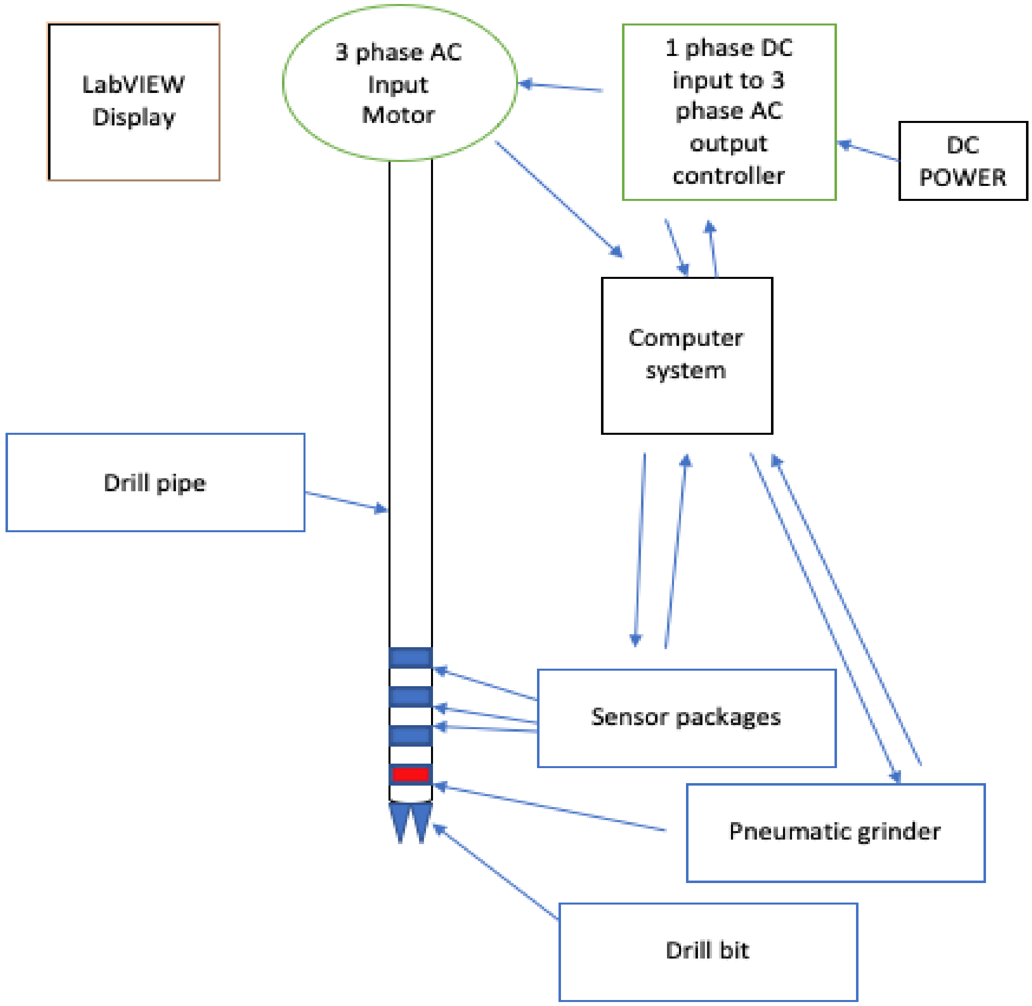

Figure 8: Schematic representing control system

The drilling optimization function will be Mechanical specific energy (MSE). Using minimum MSE rather maximum ROP for optimization purposes can avoid several drilling problems resulting from undesired forces/vibrations. These problems include bit whirling, bit bouncing, bit balling, strike-slip and interfacial severity. The controlled parameters to main minimum MSE are WOB, rpm and torque.

$$MSE = \frac{Total\ iput\ energy\ (vertical + rotation)}{Volume\ of\ rock\ removed}$$

$$MSE = \frac{WOB}{A_{bit}} + \frac{2\pi * RPM * T}{A_{bit} * ROP}$$

Where:

MSE = Mechanical Specific Energy (psi)

WOB = Weight on Bit (lb)

RPM = Revolutions Per Minute

Torque = Rotational torque (in-lb)

A_{bit} = Cross sectional area of bit (in^2)

ROP = Rate of Penetration (in/hr)

6. Budget

The expected expenses are included in table 4. The table has the main planned purchases detailed while the minor ones are under miscellaneous category. A contingency of $ 2000 is added in case of failure of our design plan A or failure of certain components.

Table 4: Estimated budget expenses

Income		
UND Budget Allowance	$ 10,000.00	
Total Income		$ 10,000.00
Expenses		
AC Drive Motor (Est.)	$ 300.00	
VFD Controller (Est.)	$ 200.00	
Stepper Motor (Est.)	$ 250.00	
Stepper Controller (Est.)	$ 150.00	
Dye Grinder	$ 17.15	
Sensors	$ 200.00	
Misc. (Est.)	$ 1,000.00	
Total Expenses		$ 2,117.15
Contingency		$ 2,000.00
Net Funds Remaining		$ 5,882.85

Equations

Normal Stress: $\sigma = \frac{F}{A}$

Shear Stress: $\tau = \frac{V}{A}$

Bending Stress: $\sigma = \frac{M\,c}{I}$

Torsional Stress: $\tau = \frac{T\,r}{J}$

Principal Stress: $\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\tau_{xy}^2 + (\frac{\sigma_x - \sigma_y}{2})^2}$

Eigenvalue Buckling $F_c = \gamma\, F$

Bernoulli's Equation: $P_1 + \frac{\rho\, v_1^2}{2} + \rho g h_1 = P_2 + \frac{\rho\, v_2^2}{2} + \rho g h_2 + h_l$