Automated Drilling Rig

Drillbotics 2016

University of Houston

Petroleum Engineering Department

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Our sincere thanks go to Dr. Robello Samuel and Mr. Ankit Mirani for helping us throughout the process of designing this rig. We would like to thank the University of Houston SPE Student Chapter for helping us participate in this competition.

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1. Introduction `

With prevailing downturn in oil prices, it has become inevitable to cut development cost in any possible way. In the expenditure cycle, drilling costs are the most important and volatile, thus it should be a priority to reduce the drilling cost to make the oil production viable even with low prices. Automated drilling is key to drilling a wellbore more efficiently and effectively. Drilling Automation improves the drilling efficiency through process improvements, optimized Rate of Penetration (ROP), consistent hole quality and overall drilling performance. Our Aim while designing this rig is to build a completely automated, safe, accurate and low cost drilling rig.

2. Rig Design

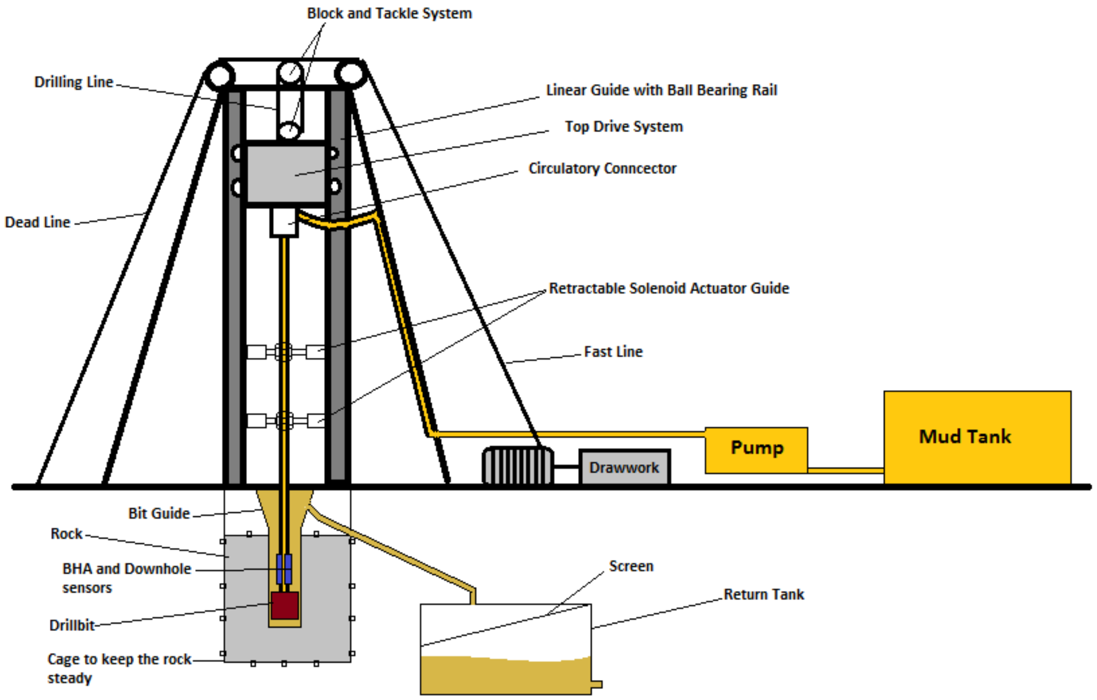

Fig 1: Basic Design (Not to scale)

2.1 Rig Structure

The rig was designed based on the contemporary rig designs to make it as realistic as possible. Our main objective was to reduce the cost while increasing the efficiency. We explored two types of rig structures like:

- 3D Rectangular Structure
- 3D Trapezoid Structure (Cross Sectional area decreasing with increasing height)

After exploring advantages and disadvantages of both structures we decided to go with the trapezoidal structure. Most important reasons behind selecting the trapezoidal structure design were: reduced cost due to application of less material, more comparable with current rig designs and better wind load handling capacity.

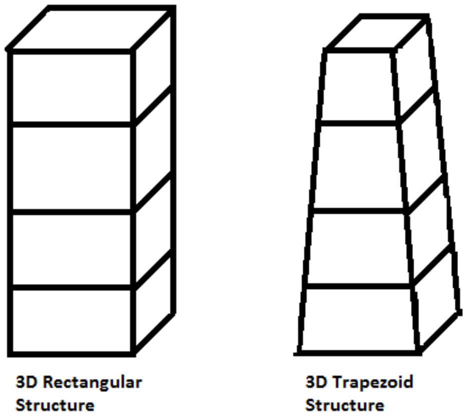

Fig 2: Basic 3D Rectangular Structure and 3D Trapezoid Structure

2.2 Hoisting System

Hoisting is one of the most important functions of a drilling rig. Hoisting is defined as system used on a drilling rig to perform all lifting activities. These activities include pulling out of the hole, running in the hole, lowering the drillstring for drilling etc. Importance of these activities make Hoisting one of the most important part of the drilling system. There are many possible systems that can be used for an automated rig. Major components of the hoisting system are:

- The Derrick
- Drawwork
- Block and Tackle Sytem
- Hooks, elevators and weight indicators

Drawwork reels in and out the drilling line in controlled fashion to lower or raise the travelling block and provides the weight on bit. Block and Tackle system has following advantages over other systems that can be used to raise and lower the drillstring:

- Ease of application
- Application of pulleys reduces effective weight to be pulled by the drawwork reducing torque, horsepower required
- Gives the system adequate control over the hoisting to effectively control the weight on bit

Features of the Hoisting System:

- Fast line from draw works to crown block
- Pulley on the travelling block
- dead line to surface
- Linear Guides with ball bearing roller slider used as railing guides
- Solenoid Actuator Guides to be used to reduce the vibrations. Actuator Guides connected to a sensor system, guide retracts if travelling block is close

Fig 3: Linear Guide Ball Bearing Rail

Fig 4: Solenoid Actuator

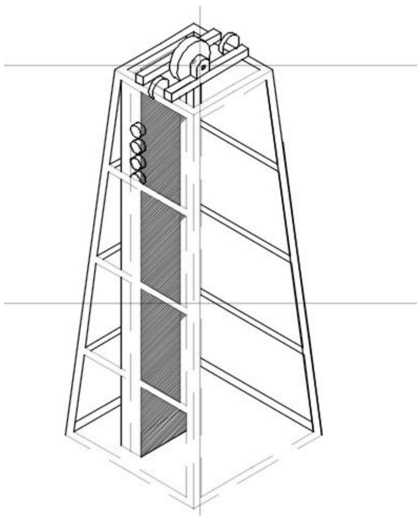

Fig 5: Derrick and the Hoisting System

The hoisting system shall consist of a 90VDC 144 RPM Gear Motor to drive the draw works system and shall operate at 200 ft-in (1/2hp, 372W). The gear motor will be powered by a 90V DC Drive system with controls via the Data Acquisition board to the main system computer.

Telemetry for the Draw Works system will consist of a clamp-type Hall Effect current sensor to monitor power input and efficiency and a load cell to monitor WOB with a maximum load rating on the load cell of 300lb. A laser displacement sensor will be installed to accurately detect vertical displacement during drilling operations.

2.3 Circulatory System

Drilling mud is a vital part of the drilling operation. It's used to cool, lubricate and support the bit and the drilling assembly and to remove cuttings from the well. The mud circulation system is used to reuse the drilling mud. The popular components of the circulatory system are shale shaker, vacuum degasser, desander, desilter, decanter centrifuge and the mud pump. The primary focus in designing an efficient circulatory system for our model was to transfer the mud into the rotating drill string. The rotational motion of the drill string in our model was achieved with the help of a motor. The diagram shown below is what our circulatory system is designed as:

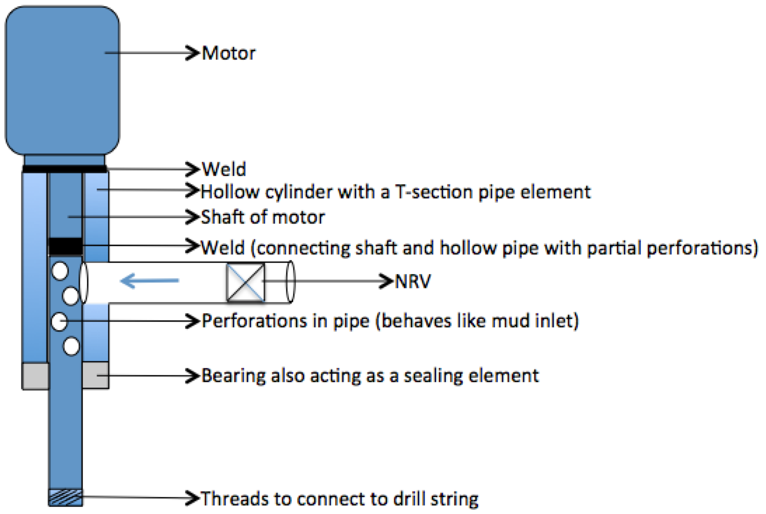

Fig 6: Circulation connector (Acts as a passage for the mud from Standpipe to the drillstring)

As per the model mud is pumped through the T-section (as shown by the blue arrow). The shaft of the motor is welded to a hollow pipe, which is partially perforated. A hollow cylinder with bearing is welded to the outer motor housing, where as the bearing isolates the perforated to the un-perforated zone of the pipe. The shaft rotates and further translates this motion to the hollow pipe. The end of this pipe is threaded to connect further to the drill string. Hence, the cylindrical element with the bearing remains stable while the hollow pipe rotates. When the mud is pumped, it enters via the static T-section into the hollow cylinder, which keeps on rotation due to the shafts rotation, but with the perforations the mud is transferred to the pipe. A Non Returning Valve avoids the flow back of this mud.

As mud, we decided to use water to drill the well. Other mud systems considered were, Water based Mud, Oil based mud, Polymer Mud, Air, Foam. For all of these other than

Air and foam, it is very likely that the density of system is higher than the fracture gradient resulting in loss circulation. This can make the rock unstable and result in a bad quality hole. One of the most important reasons not to use specialized mud was that the drilling operation to be performed will require unknown quantity of mud, if we decide to go with a mud system, we have to incorporate the solid removal systems and re-circulate the mud which will increase the cost. Main problem with using air or foam to drill the well is that air and foam both requires specialized equipment to achieve a controllable flow which will increase cost of the operation. Primary objectives of using a mud is to lift the cuttings and cool the bit. Application of Air and Foam fails to effectively achieve these objectives. On the other hand, advantages of using water are:

- Cost
- Availability- Don't have to re-circulate, high quantity of water readily available. This negates use of solid removal devices
- Safety - No hazardous chemicals used
- Easy to pump
- Water can effectively cool the bit and lift the cuttings
- Density of water is significantly less than specialized muds and more than Aerated muds. This reduces possibility of Loss circulation

The water coming out from the annulus with cuttings is taken out from the return port at the bit guide. Water pressure reduces to almost zero because of pressure losses in the drillstring, annulus and bit. Water leaves the annulus from the return port and goes to the return tank where a medium-fine mesh screen removes cuttings from the water. The returned water is still contaminated and cannot be used again. The returned water can be further purified to remove the fine particles and it can be reused. This reduces environmental impact of discarding the used fluid which is one of the most important part of a drilling operation.

The circulatory system shall make use of a 1.5hp pump motor with an attached pump roller rated at a maximum of 10gpm and 300psi. The system shall be controlled by a 1.5hp 115VAC input 230VAC output VFD module which is connected to the main system computer via the Data Acquisition board.

Telemetry for the circulatory system shall include an inline pressure transducer to detect pipe pressure and a flow meter to measure GPM; both sensors are connected to the main system computer via the Data Acquisition board.

2.4 Top Drive System

The Top Drive system shall consist of a 276 RPM 230VAC Gear Motor rated at 105 lb-in (1/2hp, 372W). The gear motor will be powered via a 1hp rated VFD with 115VAC input 230VAC output, controlled by the main system computer through connections via the Data Acquisition System.

Telemetry for the Top Drive system shall include an inline torque transducer with a maximum rating of 200 lb-in and an optical RPM sensor capable of detecting up to 300RPM.

2.5 Bottom Hole Assembly

The BHA will consist of a telemetry unit which includes a 3-axis accelerometer and Bluetooth transmitter which can communicate with the Data Acquisition board. An Arduino shield module will be modified to fit within the drill string geometry and shielded from vibration and liquid damage. Possible designs include an in-line BHA with a rigid, shielded circuit board or a shielded flex circuit.

2.6 Control System Architecture

The automated drilling rig shall be modelled after the architecture defined in the figure below. In the software layer, three parallel systems which handle visualization and storage of data, data acquisition, and control of the drilling rig will operate the system. Only the Data Acquisition and Control subsystems will have access to hardware via the hardware abstraction finite state machine, with priority interrupt access given to the control subsystem should there be a need for immediate change in the system. The control system shall include all logic required to maintain steady drilling operations with options for automatic drilling termination given a time limit, target depth, or triggered safety alarm.

Data visualization will be presented in real-time via the main system computer’s display, with an option to develop real-time display of data via the web should time permit. Visualization of data shall include a tabbed dashboard with sensor telemetry readings vs. time (current, pressure, torque, RPM, GPM, etc.), ROP vs. time, WOB vs. time.

In the hardware layer, a Data Acquisition board (DAQ) capable of digital and analog I/O as well as Bluetooth transmission will connect to the Top Drive, Hoisting, Bottom Hole Assembly (BHA), and Circulatory systems.

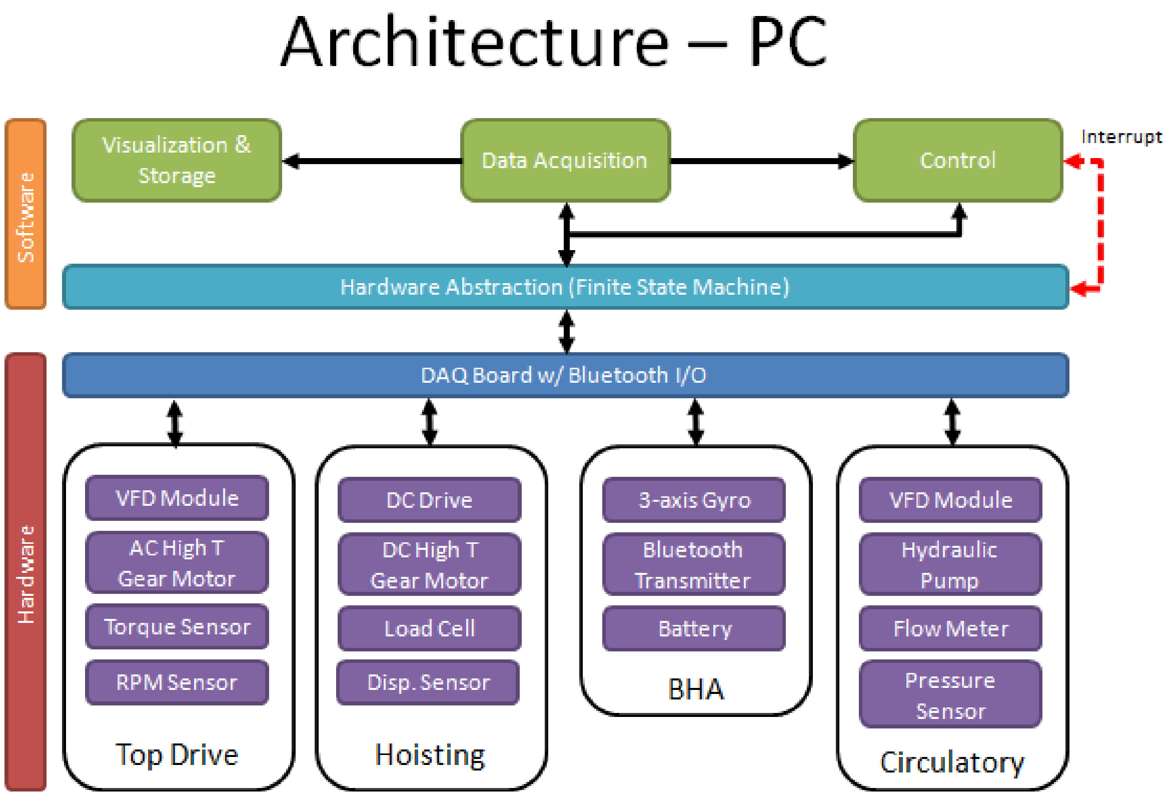

Fig 7: Control System Architecture

2.7 Sensors

Table 1: Type of Sensors to be used and Location

Type of Sensor	Location
RPM	Top Drive
Torque	Top Drive
Hook Load	Drilling Line
Block Height	Optical Sensor on the Linear Guide or Optical sensor at the drawwork
Accelerometer (Inclination, Azimuth & Downhole Vibration)	BHA
Flow Meter	Flow line

2.8 Calculated Parameters

Table 2: Parameters Calculated from the Parameters Recorded at Sensors

Parameter	Parameter from Sensor
Depth	Block Height
ROP	Block Height
WOB	Hook Load
Dogleg	Inclination, Azimuth
Torsion	Inclination, Azimuth
Wellprofile Energy	Inclination, Azimuth, Dogleg, Torsion
Drag & Torque	Inclination, Azimuth, WOB, RPM
Effective Tension	Inclination, Azimuth, WOB, RPM, Drag & Torque
Theoretical Bit Wear	ROP, WOB, RPM

2.9 Data Storage and Data Visualization

Data will be stored from the Data Acquisition Board locally in a drive as it gets recorded. Figures below show basic design of the software where data will be portrayed and analyzed.

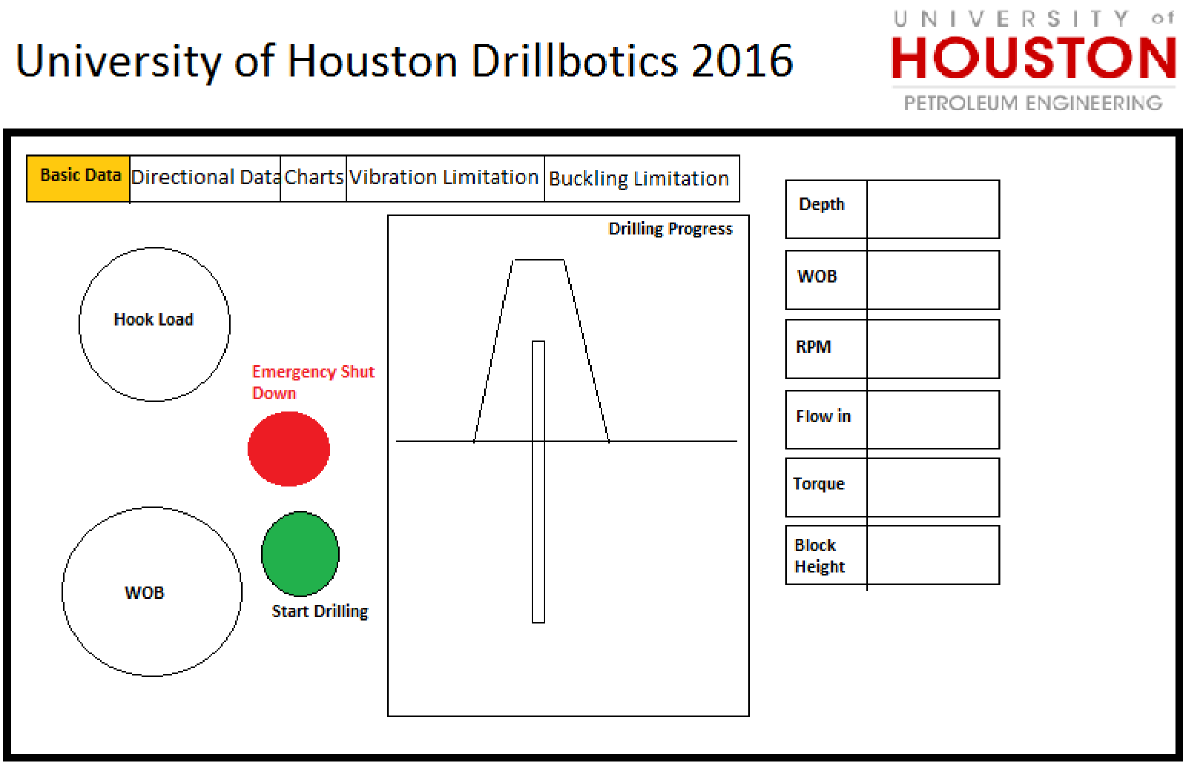

Fig 8: First tab of the Software portrays the basic drilling info taken directly from the Sensors. It also shows drilling progress as a real time diagram the data gets updated as drilling progresses. One of the most important factor here is Emergency Shut Down button which manually shuts down all operations

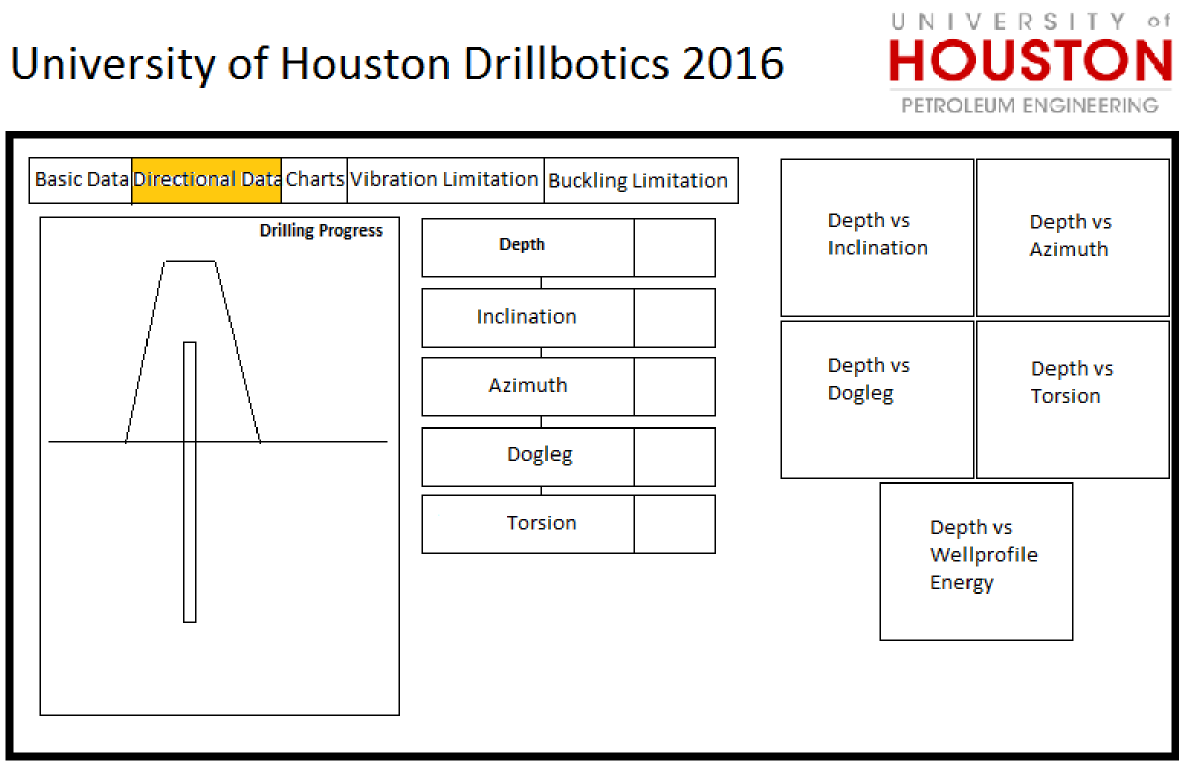

Fig 9: Second tab of the software portrays the directional drilling data like inclination and azimuth, it also contains plots of inclination, azimuth, dogleg, torsion and well profile energy-which indicates smoothness of a wellbore- with depth

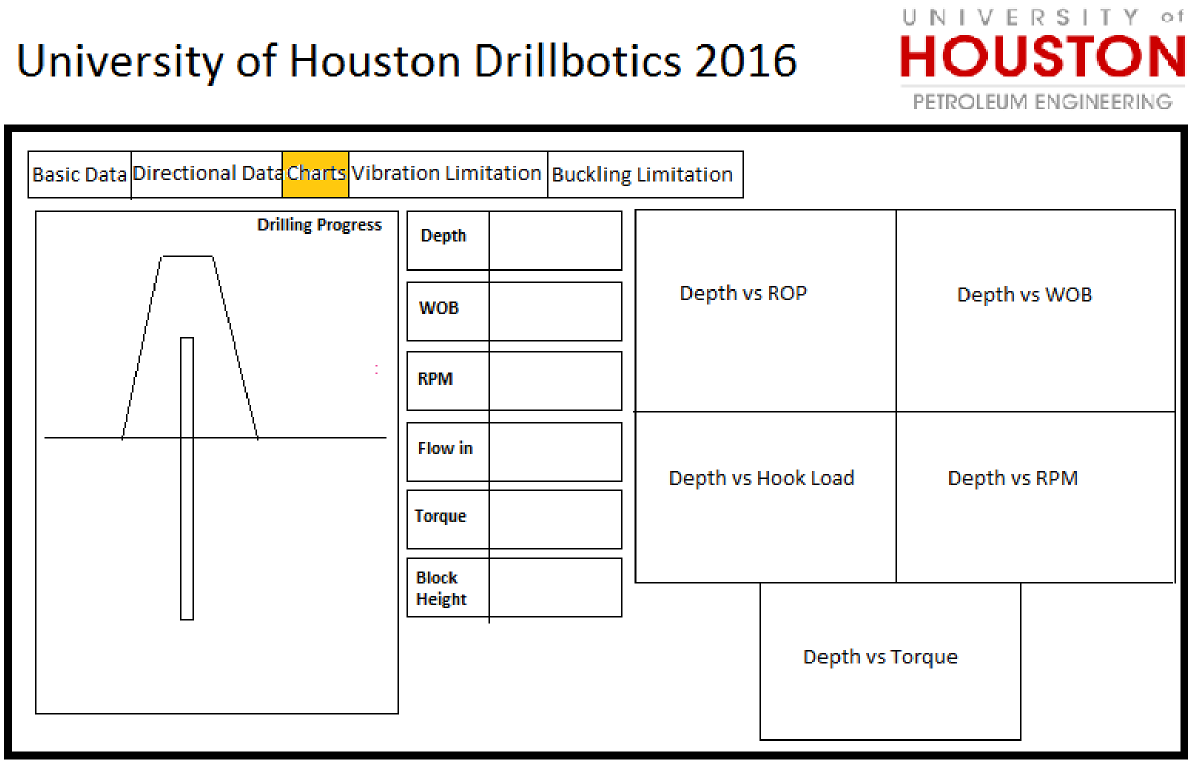

Fig 10: Third tab of the software contains plots of all basic drilling parameters with depth. These plots makes it easier to identify and mitigate a problem

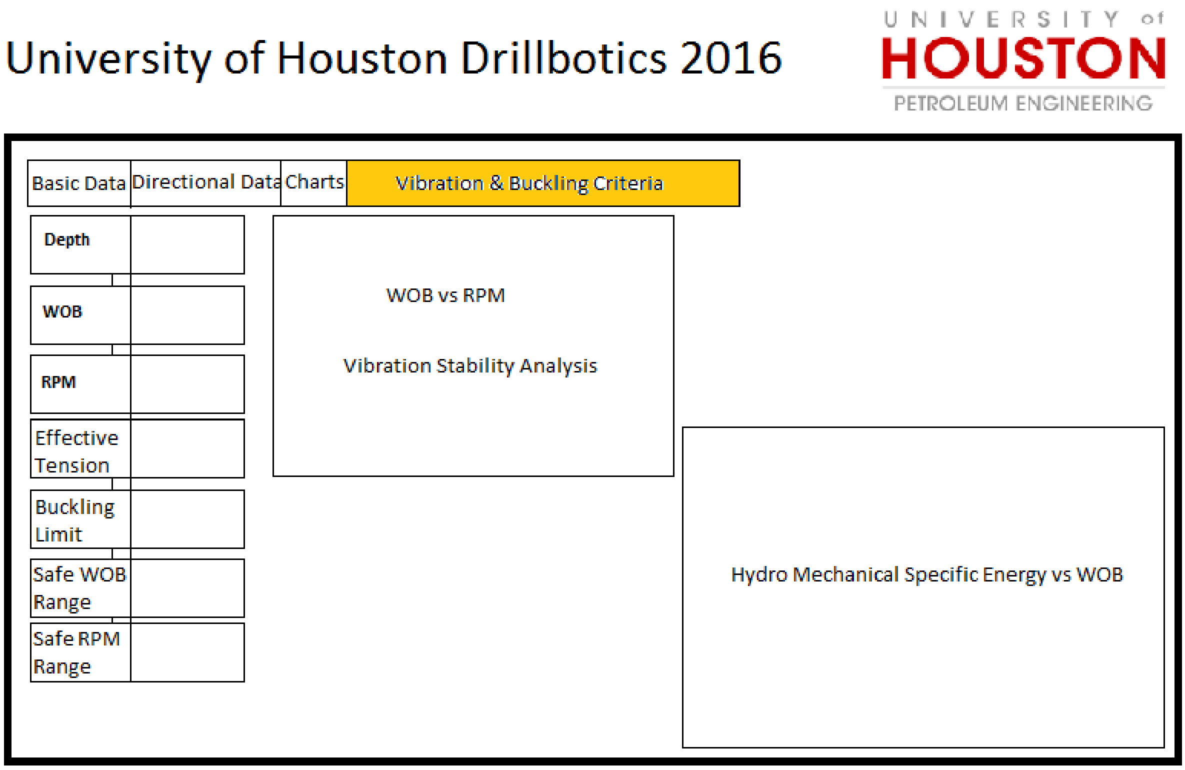

Fig 11: Fourth and final tab of the software takes depth and other data from the first tab and performs calculations to get vibration stability plot- WOB vs RPM plot for current depth, and gives a range of WOB and RPM which are safe for current depth to avoid both vibration and buckling.

3. Mechanical Control Systems

To design an automated drilling rig, it is very critical to control mechanical processes that can harm the effective drilling process like Buckling, Vibration and Bit wear. Proper control of these events will make a better hole much faster.

3.1 Buckling Control

Drill pipe buckling is caused by applying too much force or weight on top of the drillstring. Increased WOB decreases the effective and true tension in a drillstring. Buckling limit is defined by Paslay Buckling Force.

$$Paslay\ Buckling\ Force\ F_P = \sqrt{\frac{EIw_c}{r}}$$

$$w_c = \sqrt{(w_e sin\alpha + F_b\kappa_\alpha)^2 + \left(F_b sin\alpha\kappa_\varphi\right)^2}$$

Where,

$F_P = Paslay\ Buckling\ Force$

EI = Pipe Bending Stiffness

w_c = Contact Load

w_e = Buoyed Weight

α = Inclination

φ = Azimuth

$\kappa_\alpha = Angular\ Curvature$

$\kappa_\varphi = Torsional\ Curvature$

Buckling force creates a limit to the effective tension. If effective tension (F_e) is above the Paslay Buckling force, the drillstring is remains unbuckled. If effective force is below the Buckling force, the drillstring is buckled. Severity of buckling is defined by relationship of effective tension and Buckling force.

Table 3: Buckling Criteria

$F_e < F_P$	No Buckling
$F_P < F_e < \sqrt{2}F_P$	Lateral (Sinusoidal) Buckling
$\sqrt{2}F_P < F_e < 2\sqrt{2}F_P$	Lateral or Helical Buckling
$2\sqrt{2}F_P < F_e$	Helical Buckling

3.2 Vibration Control

Drillstring vibrations are leading cause of drillstring component failures. Drillstring vibration result in MWD failure, drillstring twist off and washout, Premature bit damage and reduction in ROP. Basic drillstring and drill bit motions can be divided in three basic vibration categories:

- Lateral
- Torsional
- Axial

Thus, it is vital to understand and mitigate drillstring vibrations. Standard method used to reduce vibrations is minimizing the mechanical specific energy. But, mechanical specific energy fails to identify vibrations at high WOB and RPM. Here, to identify WOB, RPM ranges where torsional vibrations can take place, we are using Dynamic Stability Approach defined by Dunayevsky et al (1998). This method depends on bit parameters, drillpipe stiffness. It defines conditions under which drill bit rotation is stable. Dunayevsky et al (1998) also defined criteria for bit lateral motion of the drill bit is stable.

Torsional Vibration Stability conditions: The bit will have stable torsional motion if all four conditions mention below are fulfilled.

$$a_1 = \frac{\kappa_p}{J_T} - \gamma\left(\left(\frac{Wf_t}{J_B}\right)e^{-\gamma\Omega_o}\right) > 0$$

$$a_4 = \frac{k\kappa_i}{J_T J_B} > 0$$

$$a_1 a_2 - a_3 > 0$$

$$a_1 a_2 a_3 - a_3^2 - a_1^2 a_4 > 0$$

Where,

$$a_2 = \frac{k}{J_B} + \frac{k+\kappa_i}{J_T} - \left(\frac{\kappa_p \gamma W f_t\left(e^{-\gamma\Omega_o}\right)}{J_T J_B}\right)$$

$$a_3 = \frac{\kappa_p k}{J_T J_B} - \frac{k+\kappa_i}{J_T}\gamma\left(\frac{Wf_t}{J_B}\right)e^{-\gamma\Omega_o}$$

Lateral Stability Criteria:

The bit will have stable lateral motion if:

$$W \geq \frac{\mu m r_o \Omega_o^2}{\eta\left(C(1+\mu^2)^{0.5} - D\right)\left(f_o + f_t e^{-\gamma\Omega_o}\right)}$$

Application of Dynamic stability approach with bit wear criteria mentioned in the next section and Hydro-mechanical specific energy creates a robust model with more focused

WOB and RPM ranges for different depths. These ranges give us optimum WOB and RPM which will make the automated drilling operation more smooth and effective. The Hydro-Mechanical Energy mentioned above can be defined as:

$$HMSE = \frac{WOB - \eta_m F_j}{A_B} + \frac{120\pi NT + 1154\eta_m \Delta P_B Q}{A_B ROP}$$

It is apparent from this equation that, HMSE depends on bit parameters, WOB, flow t is also apparent that lower HMSE corresponds to higher ROP.

3.3 Bit Wear Control

Model used to reduce the bit wear was proposed by Mirani et al (2015). This model is based on ROP model of Motaharri et al (2010). For a perfect cutting removal from a PDC bit, ROP was defined as follows:

$$ROP = W_f \left(\frac{G_o . RPM^{c1} . WOB^{c2}}{D_B \sigma} \right)$$

This equation of ROP takes into the account bit characteristics, compressive strength of rock being drilled and drilling parameters. In this equation, $W_{f,,}$ wear factor is defined as:

$$W_f = 1 - \left(\frac{\Delta BG}{8} \right)$$

$$\Delta BG = C_a . \Sigma_{i=1}^{n} \left(RPM^{c3} \left(\frac{WOB}{1000} \right)^{c4} \left(\frac{\sigma}{1000} \right) x_i \right)$$

For a given allowable change in bit grade, corresponding change in ROP can be calculated easily. These theoretical values gives us another cutoff for WOB and RPM ranges. Flowchart shown below represents the algorithm that will be used to get safe and optimum values of WOB and RPM.

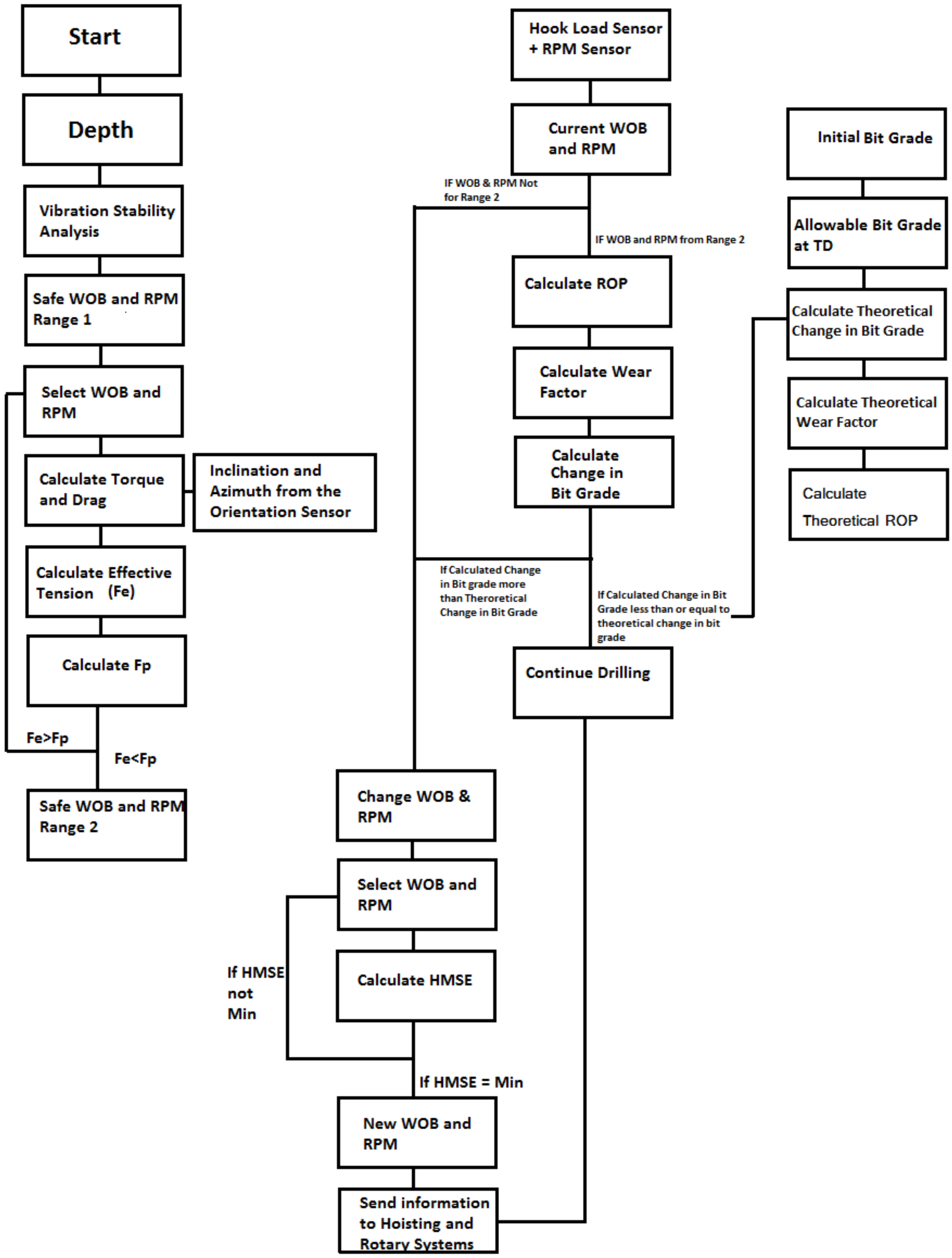

Fig 12: WOB and RPM Selection Flow Chart

4. Directional Drilling

In 2016 Drillbotics, one of the most important challenge was to design a system using which direction of the drill string can be controlled. We looked at all deviation tools used currently like Mud Motor and Rotary Steerable System (RSS) and concluded that for the current challenge application of RSS would be more beneficial as it will give us continuous and more accurate control on the direction of the well.

One of the major problems while designing the RSS for our system was in designing a downhole tool. To overcome this challenge we decided to use surface control instead. As length of hole to be drilled is shallow, direction at the drillbit can still be controlled accurately from surface.

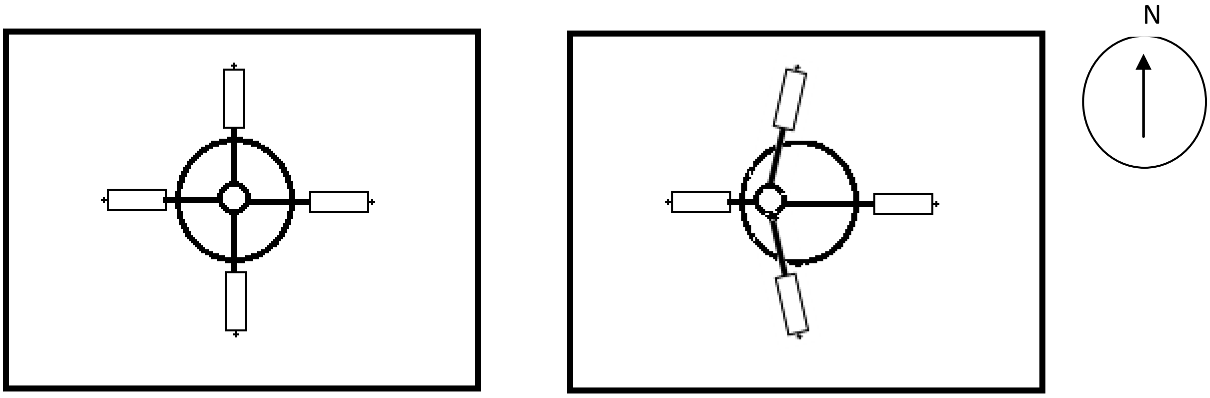

Fig 13: Directional Control System

The Directional control system consists of four linear actuators linked with the orientation sensor. If the bit starts deviating towards West, the actuator on East direction gets activated and pushes the drillstring towards West. This creates a fulcrum point for the drillstring at surface. The fulcrum forces the bit towards East countering the direction to bring it back to vertical.

Using this system we can effectively desing a RSS at surface and accurately control direction of the well while drilling further creating a smoother hole.

5. Costs

Cost summary of all equipments used is as follows:

Table 4: Financial Estimates (Tentative)			
Sensors			
No	**Item**	**Cost**	
1	RPM	$180	
2	Displacement	$450	
3	Flow Meter	$1,000	
4	Current Sensor	$20	
5	Load Sensor	$530	
6	Pressure Sensor	$140	
7	Torque Transducer	$300	
Controller DAQ			
	Item	**Cost**	**Type**
8	LabJack T7-Pro Data Acquisition Board	$499	DAQ
9	Rascal Micro	$149	MicroController
Motor - Pump			
	Item	**Cost**	**Remark**
10	90V 200W DC Gear Motor	$100	Secondary Hoisting Motor
11	230VAC Gear Motor	$800	Rotary Motor
12	90V 1/2HP DC Gear Motor	$800	Preferred Hoisting motor
13	Roller Pump, 300PSI max, 22GPM	$200	Circulatory Roller
14	Pump Motor	$230	Circulatory Motor
15	AC VFD	$250	Rotary VFD
16	90V DC Drive	$260	Hoisting DC Drive
17	1.5hp AC VFD	$200	Circulatory VFD

BHA			
	Item	**Cost**	**Type**
18	Accelerometer w/ Bluetooth Transmitter	$25	Control Board
19	Flex Circuit Prototyping	$300	Prototyping
20	Raspberry Pi 2 Model B (3 pc)	$120	Micro Controller
Actuators			
	Item	**Cost**	**Remark**
21	Solenoid Actuators (8 pc)	$80	To be used as Actuator Guides
22	Linear Actuators (4pc)	$300	To be used in Directional Control
Miscellaneous			
	Item	**Cost**	**Remark**
23	Stainless steel (60 ft)	$75	For Basic Rig structure and other requirements
24	PVC Pipe	$50	For flow and wiring
25	Rubber Pipe	$30	Flow from standpipe to top drive
26	Fine Mesh	$50	To clean the return water
27	Wires	$50	
28	Tools	$150	Drill, Cutter
29	Labour Cost	$1,000	Welding, Fabrication
30	Other	$662	Other expenses
	Total	**$9,000**	

6. Arrangement of Finances

Arranging finances for the second phase is one of the toughest tasks for the competition especially during this downturn. As of now, we don't have any sponsorship. But if we get selected to the second round, our strategy to finance the competition is as follows:

- Our major sponsorship will come from the companies. Once we get selected for the second round, we can go to various companies and ask for funds. We already have a list of probable sponsors in place and we are continuously looking for sponsors
- We are planning several workshops in drilling with Dr. Samuel. These workshops will be open to Sindustry professionals and all funds generated from these workshops will go to UH SPE Drillbotics Team
- We will seek help from The University of Houston Petroleum Engineering Department.
- We will seek help from AADE UH Student chapter, UH SPE Student chapter and other student run organizations to make this a joint project.

7. Conclusions

Designing the drilling rig for this competition was a difficult task which we have tried to accomplish. Our main concerns while designing this rig were to ensure safe working environment for everyone involved if we get to build it in Phase 2 of the competition and to make sure that we plan everything in a strict budget.

Rig designed by us can successfully:

- Raise, lower and rotate the drillstring
- Circulate and discard water which is to be used as mud to cool the bit and circulate out the cuttings
- Records, calculates and displays all drilling data.
- Identifies problems like Vibration, bucking and deviation from original path and takes actions to counter or mitigate it.
- Drill a vertical or directional well in any rock.

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