



SCHULICH
School of Engineering

AUTONOMOUS DRILLING RIG

Drillbotics 2016-2017

TEAM

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Introduction

It is our, University of Calgary team, first time to participate in Drillbotics competition. Our design was found based on the guideline, and other teams' lessons learned. During the first several weeks, strengths and weaknesses of the previous year models were discussed and analyzed. The final design came with the idea of the counterweighting to create the Weight On Bit (WOB) as desired. Furthermore, this method is expected to reduce a power-requirement from drawworks. The pneumatic actuator was employed to balance the drilling tower because of its versatile and accuracy. This actuator is selected because its high resolution, and therefore it can provide a precise directional steering. The sensor system was developed based on the actual drilling rig. However, the minor details were added to observe our objective functions; (i) the smooth vertical hole condition, and (ii) speed of penetration. To this end, this design is expected to initiate the new idea of the drilling rig and achieve the competition goals.

Design choices

Primary components

The most important part of the Wibble rig is the drilling tower. Most of the main components, except the mud tank, are located in this section. Therefore, a meticulous care has to be focused since the failure might arise from this particular part. Furthermore, the base of the drilling rig was formed to handle the weight of this part with the balancing force to prevent the tipping.

The pneumatic motor was picked to manipulate and support the drilling tower. This method has an accurate control-feature. Therefore, it is expected to provide a proper directional steering.

Counterweighting technique was chosen to balance and create the WOB as the optimization algorithm identify. Lastly, the top drive section, AC motor with an rpm range between 1000-3000 rpm and 5 HP, was selected to accomplish our goals; (i) hole condition, and (ii) rate of penetration. This selection was formed based on the previous UT Austin design.

Sensor

There are three essential sensor locations; (i) Bottom Hole Assembly (BHA) including the bit itself, (ii) mud system, and (iii) top drive. These choices were selected based on the critical measurements that were required to operate our tasks appropriately and safely. Sensors at the BHA are used to appraise the well path and ensure the well quality. WOB is controlled to get the designed rate of penetration and alarmed when the bit stuck situation happens. Sensors at the mud tank were planned with two purposes; (i) manage the pumping rate to carry the drilling solid out of the hole and cool down the drill bit, and (ii) make sure that our drilling bit is not overheated (temperature measurement). Finally, the top drive sensors are employed to observe; (i) motor speed and torque, (ii) top drive position (connect to the control system and pneumatic actuator), and (iii) vibration.

Data handling and visualization

The mentioned sensors in the previous section collect the data, subsequently, transfer to National Instruments LabVIEW as an integrated and display junction. This developed environment was selected because of its functions and availability. Our team visualization features are designed to be simple but contain all required data.

Mud system

In the latest model, tap water is exploited as a drilling fluid to lift the drill cutting and provide a heat transfer media to the BHA. We expect the simplified fluid should provide an adequate function with an

optimized cost. This mentioned scheme comprises of mud tank, pump, hose, swivel, drill pipe, BHA, drilling fluid return line, and tank with a mesh filter to screen out the drilling solid.

Control system

The control scheme is applied to ensure three aspects; (i) drilling operation, (ii) optimization, and (iii) safety. This system is interconnected with all other systems to guarantee the smooth operation.

Safety

The safety system is integrated with the control system and sensors scheme. Since this competition is our first experience, our conceptual idea is founded based on the lessons learned from the previous models. As stated in the previous section, the drilling tower is the most critical part; the tipping failure may happen when the system tries to balance the WOB regarding the control system identify. Therefore, in the case of the potentially tripping happen, the overall operation is ceased, subsequently, activate the alarm. Spring systems also help to balance the tower, and are placed between the tower and table around ball joint connections. In the drill bit, BHA, or drill pipe stuck situation, the sensors that are located in the drill string signal the control system to stop the top drive to prevent the pipe breakdown. For the mud system, if the rapid pressure drop occurs, subsequently meet the threshold value, the sensors will alarm, and stop the mud pump.

Structural Design:

The base of our drill rig will be a steel table capable of supporting the drilling tower and other auxiliary components. The main component of our drill rig will be the drilling tower which holds most of the components and facilitates their movement. Thus a strong design was made composed of eight 1200x40x40 mm Aluminum 8020 supports as shown in figure 1. Two 10 mm thick Aluminum sheets are also attached to the back of the 8020 supports for additional strength. Twelve 190x40x40 mm 8020 supports are placed horizontally between the vertical supports to prevent any buckling of the tower. Two 10x300x300 mm plates will be bolted onto the top and bottom of the 8020 columns.



Figure 1: 40X40 Aluminum 8020 [1]

The drilling tower is connected to the table using a ball joint. The ball joint selected will be a vital component for our design, as it will be carrying the entire load of the tower while facilitating movement in all three planes. A proposed ball joint to use for our project is a car ball joint due to its capability of handling high loads and availability. Ball joints will also be connected to the pneumatic pistons to provide movement. The tower will be moved sideways, forward and backward according to the inclination it faces.

The top drive will also be raised and lowered via draw works and a counter weight system which functions similar to an elevator to reduce power consumption.

Design Calculations:

Basic design requirement calculations were performed for the motors and pneumatics.

Draw Works:

Torque:

$$\tau = F \times r$$

τ : Torque

F : Force

r : Radius

$$r = 1" = 0.0254m$$

$F = \text{Weights of Top Drive} + \text{Drill String} + \text{BHA} + \text{Drill Bit} + \text{Counterweight}$

$$F = W_{top} + W_{string} + W_{BHA} + W_{bit} + W_{counter}$$

$$W_{top} = 70lbs = 312N$$

$$W_{string} = \text{aluminum} \times 4 \times (OD2 - ID2) \times L$$
$$= 0.098 \times 0.785 \times (0.1406 - 0.1135) \times 36 = 0.075lbs = 0.33N$$

$$W_{BHA} + W_{bit} = 8lbs = 35.6N$$

$$W_{counter} = 40lbs = 178N$$

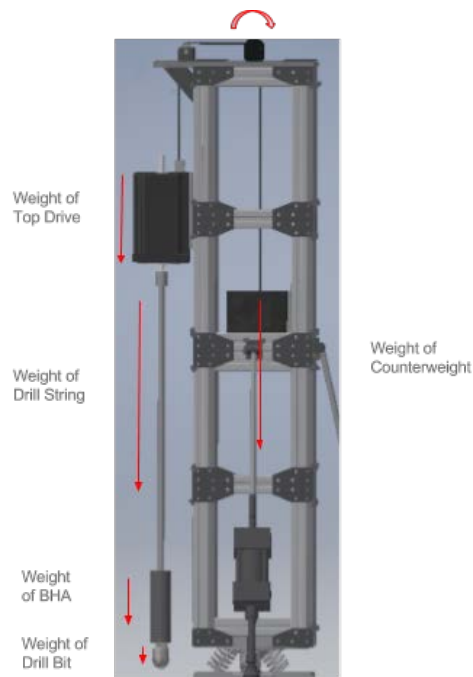


Figure 2: Free Body Diagram

Torque required by draw works is:

$$\tau = (312 + 35.6 + 0.33 - 178)N \times 0.0254m = 4.32N * m$$

Each revolution displaces the bit:

$$2 \times 0.0254m = 0.16m$$

The average velocity required to pull the bit out of the formation in 5 seconds, from bottom to surface (0.6 m):

$$V = \frac{0.5}{5} = 0.12 \frac{m}{s}$$

This requires an rpm of:

$$RPM = \left(\frac{0.12}{0.16} \right) \times 60 = 45$$

Thus, Power required for draw works motor is:

$$Power = \frac{\tau \times RPM}{5252} = \frac{4.32 \times 45}{5252} = 0.04 \text{ horsepower}$$

Top Drive:

Our Top Drive selection was based on the need for an efficient rate of penetration. The rate of penetration depends on the weight on bit, revolutions per minute and the formation hardness. From literature review, we learned that running at a low rpm will decrease our rate of penetration and a high weight on bit will increase our torque sensitivity. We based our selection of our top drive motor on the experience of previous teams in the drillbotics competition. The team from University of Texas at Austin had an AC motor running at 340 rpm and providing 0.5 HP. This selection proved to be not very effective since it was slow. Our proposed top drive motor will be an AC motor with an rpm ranging between 1000-3000 rpm and 5 HP. Based on future testing's of our top drive, adjustments can be done to the speed and power of the motor by introducing different sets of gears.

Pneumatics:

In order to calculate the required pneumatics, we placed the tower in its maximum tilt position, which is 20 degrees.

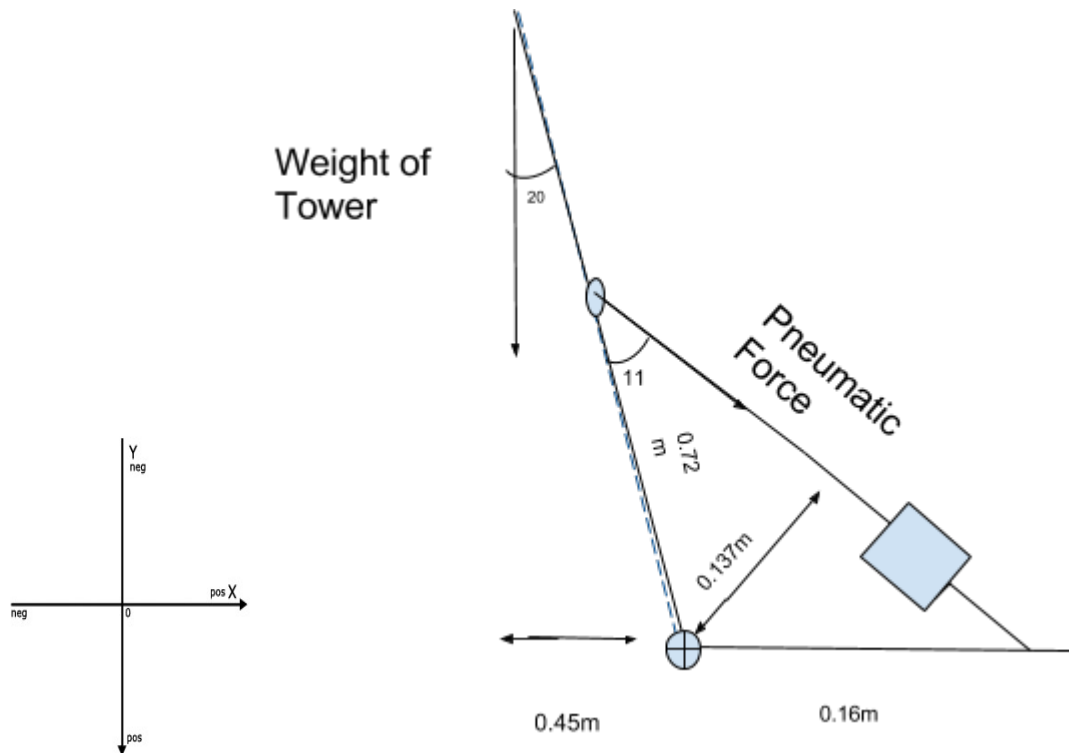


Figure 3: Diagram for Pneumatics Calculations

In order to find the required pneumatic system, an extreme case was investigated when all the components were placed on the highest point on the tower.

$$\begin{aligned}
 & \text{Weight of Tower} \\
 & = 8 \times \text{Weight of 8020 (1.2m)} + 12 \times \text{Weight of 8020 (0.19m)} \\
 & + \text{Weight of Top Drive} + \text{Weight of Draw Works} + \text{Weight of Drill Pipe} \\
 & + \text{Weight of BHA} + 2 \times \text{Weight of Aluminum Wall (1.2m)} \\
 & + \text{Weight of Upper and Bottom Plate} + \text{Weight of Counterweight}
 \end{aligned}$$

$$\begin{aligned}
 & \text{Weight of Tower} \\
 & = 8 \times (0.1321 \times 39.37) \times 1.2 + 12 \times (0.1321 \times 39.37) \times 0.19 + 50\text{lbs} \\
 & + 10\text{lbs} + 0.075\text{lbs} + 8\text{lbs} + 2 \times 2800 \times 2.2 \times 1.2 \times 0.3 \times 0.015 \\
 & + 2 \times 2800 \times 2.2 \times 0.3 \times 0.3 \times 0.015 + 40 = 225\text{lbs} = 1135\text{N}
 \end{aligned}$$

Moment:

$$\begin{aligned}
 & \text{Moment Due to Weight of Tower} = \text{Moment of Pneumatic} \\
 & \text{Force of Pneumatic} = \frac{1135 \times 0.45}{0.16} = 3139\text{N}
 \end{aligned}$$

Thus the maximum pneumatic force required is 3193 N.

Bill of Materials:

| No: | Description | Supplier | Unit Price(USD) | Quantity | Cost (USD) |
|-----------|------------------------------------|-------------------|-----------------|----------|--------------|
| 1 | 8020-40x40x1200 (mm) | 8020.Inc | 28.8 | 8 | 230.4 |
| 2 | 8020-40x40x190 (mm) | 8020.Inc | 4.56 | 12 | 54.72 |
| 3 | Back Plate 300x1200x10 (mm) | Amazon | 85 | 2 | 170 |
| 4 | Plate 300x300x10 (mm) | Amazon | 29.92 | 2 | 59.84 |
| 5 | Ball Joint | Amazon | 100 | 3 | 300 |
| 6 | Table | UofC Machine Shop | 150 | 1 | 150 |
| 7 | DrawWorks Step Motor (34D314S-LW8) | anaheimautomation | 368 | 1 | 368 |
| 8 | Drill Bit | UofC Machine Shop | 50 | 1 | 50 |
| 9 | CounterWeight 25 Kg | UofC Machine Shop | 20 | 1 | 20 |
| 10 | Linear Bearing Dia 10 (mm) | Amazon | 60 | 2 | 120 |
| 11 | Pneumatics | Parker | 150 | 2 | 300 |
| 12 | 8020 Joints | 8020.Inc | 5 | 40 | 200 |
| 13 | Pneumatic Joint | Amazon | 5 | 2 | 10 |
| 14 | ball Bearing | VXB BALL BEARINGS | 1.5 | 4 | 6 |
| 15 | Shaft | UofC Machine Shop | 3 | 2 | 6 |

| | | | | | |
|--------------|---------------------------------------|-------------------|------|---|----------------|
| 16 | Top Drive Motor (MTCP-005-3BD36) | Automation Direct | 309 | 1 | 309 |
| 17 | Pneumatic Compressor | Home Depot | 100 | 1 | 100 |
| 18 | Mud pump | Shurflo | 80 | 1 | 80 |
| 19 | pipes and tubes | Uxcell | 20 | 1 | 20 |
| 20 | Double Chain 2200(mm) | KMC | 30 | 1 | 30 |
| 21 | Gear Chain Dia 26 (mm) | KMC | 10 | 2 | 20 |
| 22 | Compress Springs | Amazon | 1.5 | 4 | 6 |
| 23 | Torque Sensor T12 square 1/4" | Interface | 3300 | 1 | 3300 |
| 24 | Temperature Sensor (DS18B20) | Sparkfun | 8 | 1 | 8 |
| 25 | Optical Encoder | Sparkfun | 5 | 1 | 5 |
| 26 | gyro (L3G4200D) | Sparkfun | 40 | 1 | 40 |
| 27 | Linear Strain Gauges SGT-3S/350- TY43 | Omega | 29 | 1 | 29 |
| 28 | Cables | Sparkfun | 50 | 1 | 50 |
| Total | | | | | 6041.96 |

Table 1: Bill of Materials

Sensors

A number of sensors will be placed throughout sections of the drilling rig to collect important information that will be used to monitor and assess the current state of the drilling process. The following section will outline the vital parameters that will be measured and the sensors applied to do so.

Top Drive Integrated Sensors

RPM and Torque

A variable frequency device will be used to measure and control both RPM and torque of the AC motor. A variable frequency device will be able to provide us the control we need of the RPM and torque while also giving us a very marginal error of about 1% in the readings, this makes it an optimal selection for this task. This variable frequency drive data will then be checked using data that will also be collected using a torque sensor. Comparing these two results will allow for very precise measurement of both RPM and torque.

Top Drive Positioning

Since we have used a combination of pneumatics and a functional draw works for movement of our top drive, in order to sense its position we will need to know both the angle it is at and the height of the unit itself. This will be done using two separate sensors, one for each task. For the angle of the drilling rig and top drive we will be using gyroscopes, this is because they are very cheap and can be very accurate especially if we were to use a combination of gyroscopes. To find out the vertical position of the top drive, we will be using an optical sensor/encoder, which since we are using a stepper motor for the movement of the top drive, will be able to figure out how many units the chain for the top drive has adjusted up or down. Since the stepper motor is going to be adjusting the chain on exact steps, this measurement of vertical height will be pretty much exact.

Vibration/Resonance

A Tri-axial accelerometer will be installed onto our top drive in order to measure for vibrations which may lead to resonance of the drilling rig structure and unsafe drilling conditions. These measurements may also be used to remove possible noise in our measurements of weight-on-bit, therefore further reducing the error associated with that measurement.

Weight-on-Bit

An S-beam load cell will be installed between the drive chain and the top drive motor in order to measure the weight-on-bit. Load cells can vary in accuracy greatly especially when comparing them over different price ranges, but overall even on the cheaper end

of the spectrum the full scale repeatability is $\pm 0.05\%$ which will be negligible for our operations.

Mud System

The mud system will also contain two different sensors to ensure that it is functioning properly. The first of which will be a flow meter this will ensure that the system is operating at the desired flow rate keeping the path of the drill bit clean and also flowing at an optimal rate to ensure that the drill bit is being cooled sufficiently. The second sensor which will be used within the mud system is a temperature probe, this will be employed on the drill bit to monitor its temperature and will be used to ensure the drill bit is not subject to overheating.

Bottom Hole Assembly

In order to get a picture of the path that the drill bit is taking through the well it is necessary to find the inclination, azimuth. This can be done using a combination of a magnetometer and a gyroscope. The downhole vibration may be found by using an accelerometer.

The sensors that are to be used to take measurements while drilling will be subject to a wide variety of temperatures and pressures, so the sensors selected should be picked to withstand the harsh operating conditions.

In order to employ any type of sensor within the bottom-hole assembly we will need to find a method that will be suitable to power said sensor within the BHA. For this we will be looking into a couple of different strategies, powered systems and telemetry systems.

Powered Systems

Powered systems can further be broken down into two subcategories, battery systems, and turbine systems. A Battery system is exactly as the name states, using a high energy density battery to power the system. The drawback of this method is that you are on the timer of the battery, and once the battery is drained the sensor will stop working. A turbine system uses the mud that is being pumped through as its source to power the system. The problem with this method would be that once the mud systems stop flowing the turbine would no longer provide power, and also for our case since our filtration systems will not be ideal, the turbine would have to be able to endure high stress of pushing through debris.

Telemetry Systems

These systems which use acoustics that transmit up the drill pipe are what is used traditionally to measure while drilling. This method would provide us with very real time measurements of what is going on during the drilling process, as it can provide data samples at astounding rates. However these systems are not cheap and require a lot of electrical work to implement successfully, and could potentially experience a considerable amount of noise from out mud systems which would need to be filtered out for the data to be useful.

In addition to power delivery we had to decide what method to employ in order to transmit data back from the bottom hole so that it would be usable to us in order to monitor what is going on. For this we have decided that we will be using a Bluetooth device in order to transmit the data from the bottom hole back up and to the raspberry pi unit, which will then allow us to display it on the computer. We have opted for Bluetooth as it is very simple to install and can transmit data at very high transfer rates meaning we will not have to worry about not being able to send the data back fast enough.

Data Handling & Visualization

In order to collect the data from all of the various sensors that are being used in the drilling rig, we will be using a combination of an analog to digital converter and a raspberry pi unit. The analog to digital converter will transmit signals at very high sample rates as there is a lot of data coming in, for this reason we have opted to use a 12 bit resolution which can deliver a sample rate of 2 Msps and above, while still remaining relatively affordable. This unit will send the data over to a computer which will then sort and visualize this data using National Instruments LabVIEW. Shown below is a simple flow sheet to display our data measurement system.

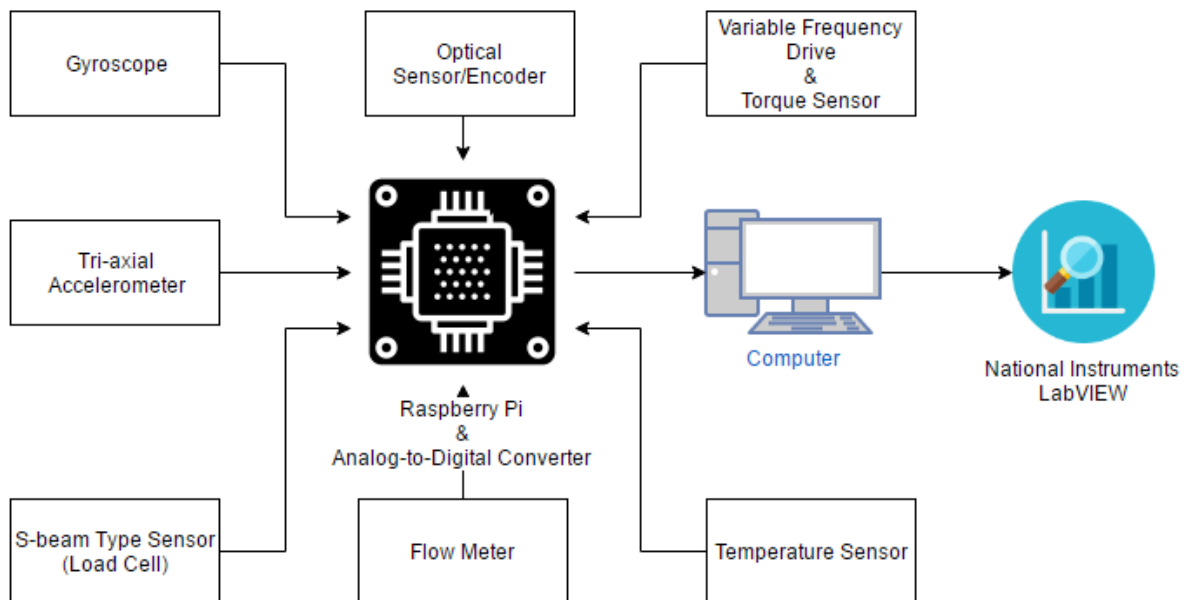


Figure 4: Data Handling Flow Chart

Mud System

The mud system is a fluid circulation system that helps keep drilling temperatures low by cooling and lubricating the bit, it also helps remove drill cuttings from the hole. The mud system consists of a tank, pump, hose, swivel, inside of drill pipe, drill bit, nozzles, mud return line, collection tank with mesh filter. The mud could just be tap water, it would be pumped from the holding tank into the drilling system then returns to the holding tank on the other side of the mesh. The mesh acts as a filter, removing rocks and other solid debris. A collection tank will be placed under the rock so if any fluids leak out, they will be collected pumped back into the holding tank.

Rig Mobility

In order to make our rig more mobile, the tower will be attached to a steel plate on hinges connected to the table. The design allows for the tower to be tilted up and down so that the table can be moved around easily when it is not drilling. The steel plate will have hinges on the table side and holes for bolts on the edge of the table. The bolts are used to hold down the plate so that the tower does not fall during drilling. In order to prevent the tower from falling too fast, there will be a piston attached to the back and an arm to hold the tower above the table. The piston will ensure the tower falls slowly and the arm will let the tower rest at an angle instead of flat on the table where it might damage other equipment. The pistons used to steer the tower will be easy disconnect/connect type so they can be moved out of place to let the tower to lean back. There will be no automatic tilting of the tower so it has to be physically lifted and lowered before and after drilling. The table will have wheels that can be raised or lowered, this lets the table sit on its legs when drilling and on the wheels when it needs to be moved.

Control Systems

This section covers our preliminary control system design and hardware. The Figure below shows the various states which the drilling rig could be in and how the link to one another.

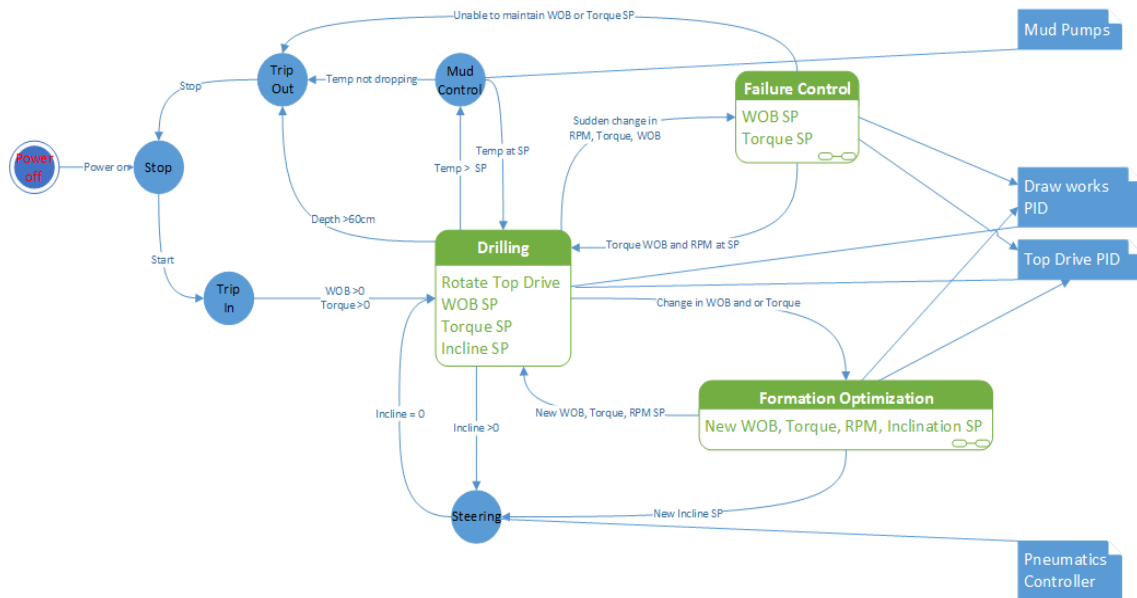


Figure 5: State System

System Integration

The control system is integrated through the use of Baseline Control

The baseline performance will be established using tuned PID control loops. It will control top drive RPM (using torque feedback), draw works speed (using WOB feedback), tower incline (using accelerometer feedback) and mud flow rate (using temperature feedback).

Performance Optimization

Once the baseline control is established as a benchmark, more advanced control strategies may be used. Some possible strategies include:

- Parameter optimization by test drilling certain rock types and manually tuning drilling parameters
- Online learning: Due to the abundance of data collected, drilling parameters and performance could be tuned using online learning.

The controller can also be programmed to determine the founder point when drilling. The founder point is where an increase in WOB will no longer increase the rate of penetration (ROP). The controller will take the ROP and WOB data and analyze it, and when there is no longer an increase in ROP with an increase in WOB the controller will set the WOB so that max ROP is achieved without using an excessive WOB given that it is less than the max WOB allowed.

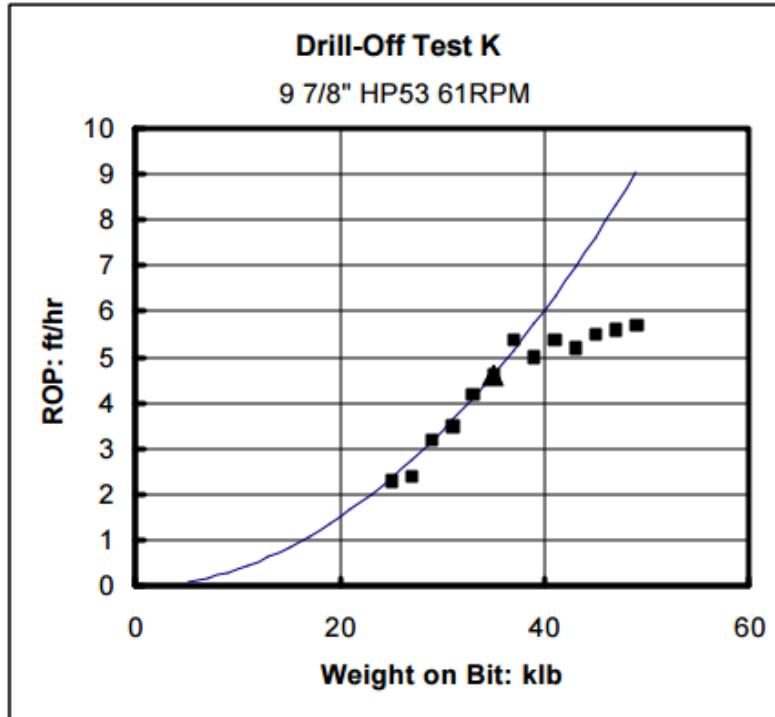


Figure 6: Variation of ROP as a Function of Weight on Bit [2]

As seen here from real data, the ROP stops increasing once the WOB reaches a certain value. The curve shows the theoretical increase in ROP as WOB increase, but that is only accurate up to the founder point.

Response Time and Sampling Frequency

The controller has to process data at an extremely fast rate so that even the slightest change is caught and processed. This is extremely important because when it is drilling and the drill bit snags on something or hits a harder formation, the controller needs to slow the top drive motor or else the drill string will fail. This sampling frequency is determined by the minimum time required for the shock to travel up the drill string to the motor.

The length of the drill string + BHA is approximately 1m long and the shock moves at the speed of sound (340m/s)

$$1m \div 340 \frac{m}{s} = 3.0 \times 10^{-3}s \text{ or } 3ms$$

The controller needs to respond in 3ms or less. So if sampling rate was at 1000hz that would give the controller 2ms to respond to the change and slow the top drive or to decrease WOB.

Model

The Inertia of the BHA needs to be calculated. The inertia of a cylinder rotating on an axis could be calculated using the following formula:

$$I = \frac{1}{2}MR^2$$

The weight of the BHA and bit was 8lb and the radius could be approximated to be 3/16in = 0.015625ft

$$I = \frac{1}{2} \times 8 \times 0.015625 = 0.0625 \text{ lb ft}^2$$

The Motor inertia was given to be 0.22 lb ft²

Also getting all the delay times from the electronic components

```

J_bha = 0.0625;           %BHA Inertia
J_td = 0.22;             %TD Inertia

T_vfd_max = 22.82;      %max torque
T_vfd_min = -22.82;     %min torque

f_cutoff_encoder = 125; %max frequency of encoder filter
f_cutoff_sensor = 1000; %max frequency of sensor
f_cutoff_vfd = 125;     %max frequency of vfd
PI_delay = 0.001;      %delay of PID Controller
vfd_delay = 0.01;      %delay of VFD
DS_delay = 0.003;      %mechanical delay of drillstring
sensor_delay = 0.001;  %delay of sensors
    
```

Now this could be simulated using a Simulink model shown below

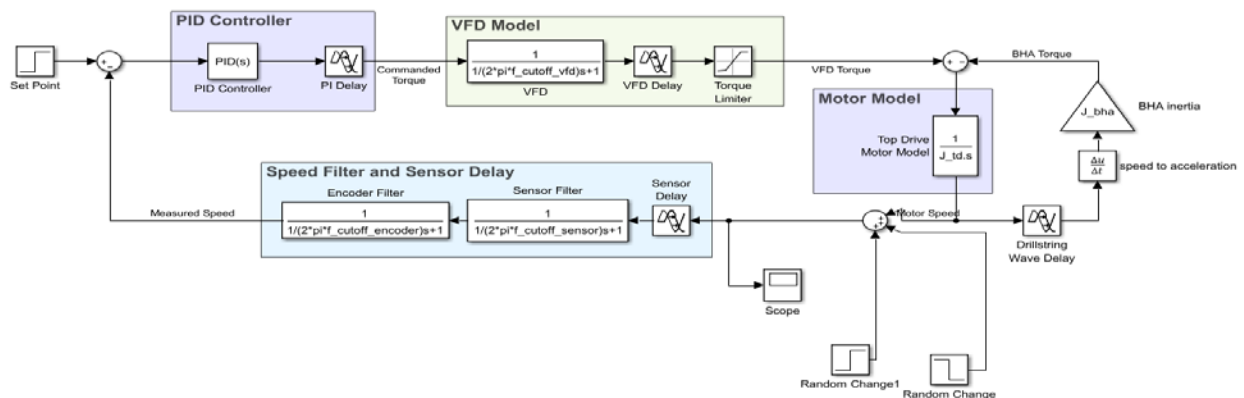


Figure 7: Top Drive Model

The motor set point was set to 15 and 2 random changes were introduced at various times to test the PID controller. Using $P=10$ $I=1$ and $D=0$ the controller's performance could be seen below.

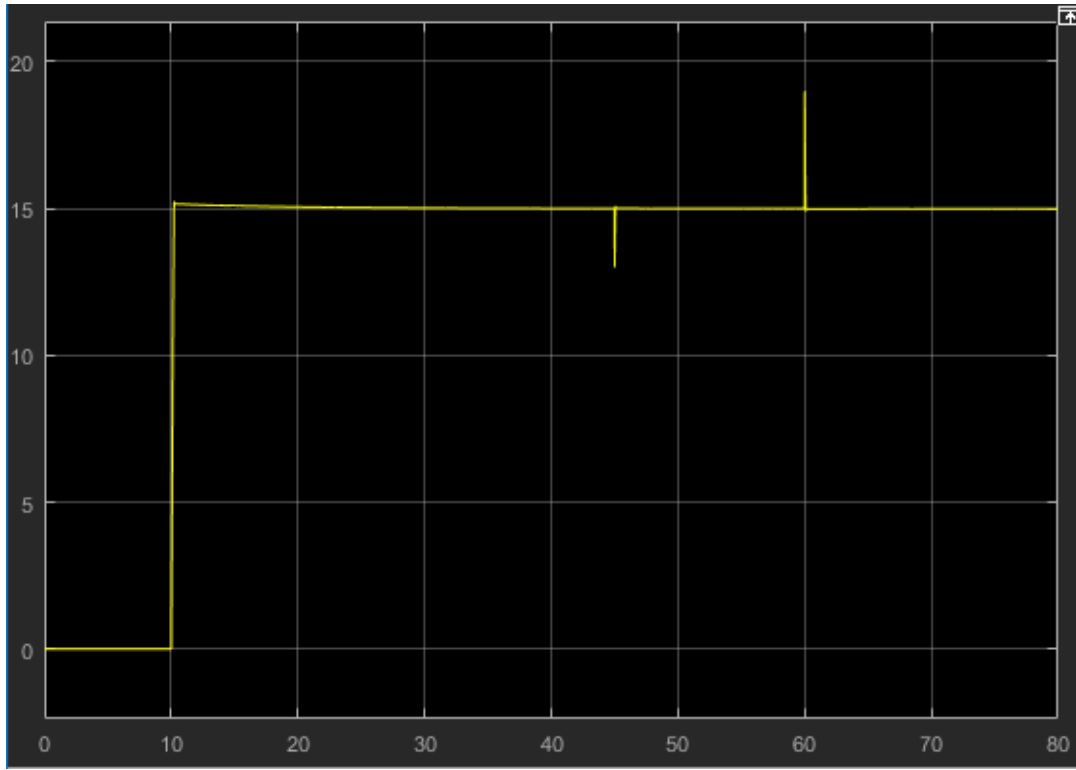


Figure 8: Top Drive Controller Scope

If there was a change that dropped the motor speed, the controller will supply more power and raise the speed back to set point. If the drill bit hits a softer formation and speed increase, the controller will lower power so the motor speed will return back to set point. This is done rather quickly if all the equipment response times are very fast.

Tower Tilt:

For the tower tilting a proposed model would be

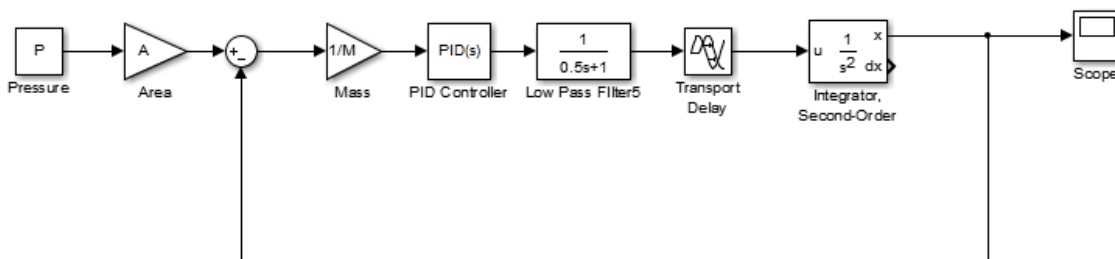


Figure 9: Tower Tilting Model [3]

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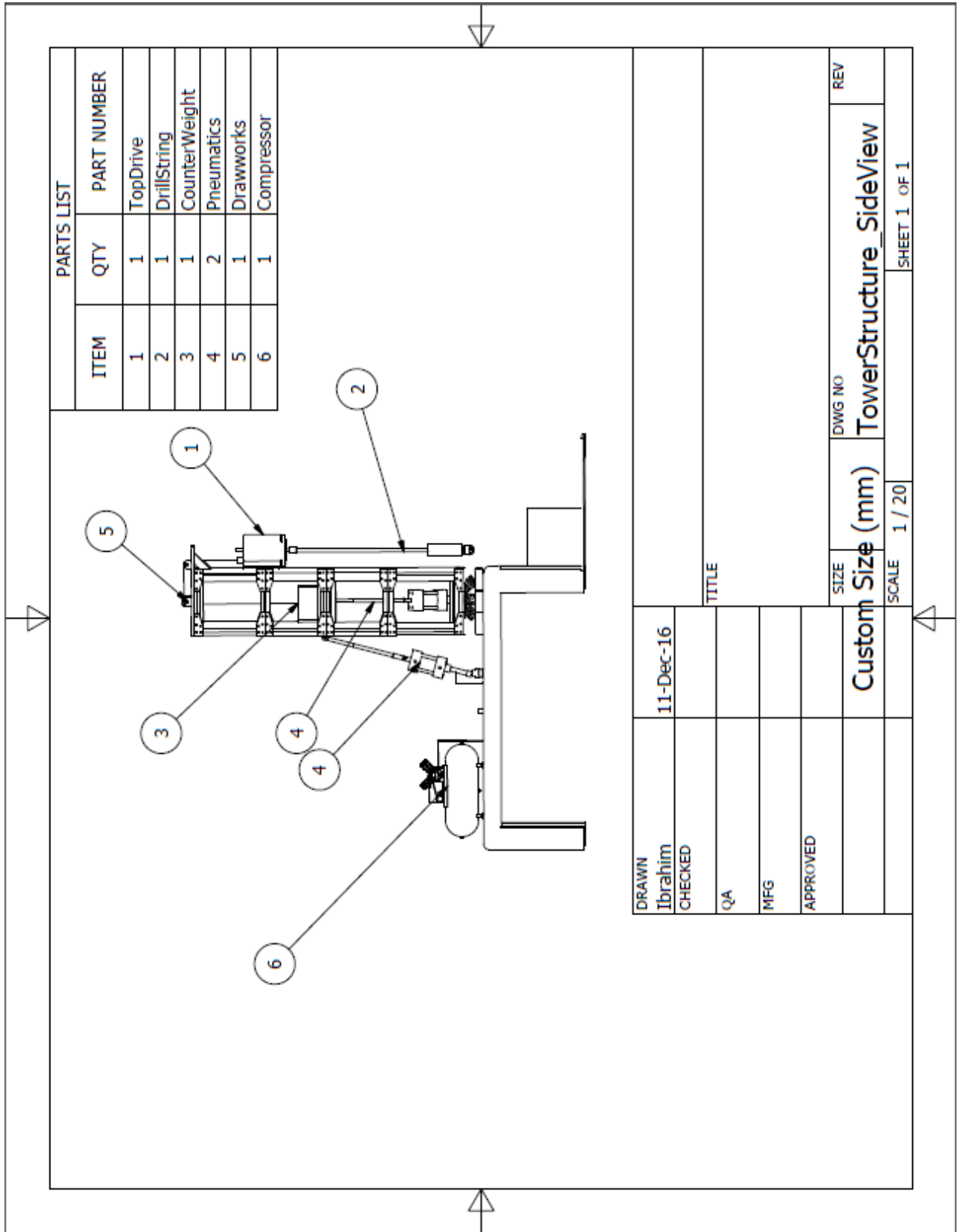
Table 1: Bill of Materials

References

[1] <http://i.ebayimg.com/images/g/hTUAAOxyzfNRv1X9/s-l300.jpg>

[2] <http://aade.org/app/download/7238830961/AADE+31.pdf>

[3] Dihovicni, Djordje, and Medenica, Miroslav , *Mathematical Modelling and Simulation of Pneumatic Systems*, Visoka tehnicka skola, Bulevar Zorana Djindjica 152 a, 11070 Serbia



| | | | | | |
|------------------|-----------|-------|-------------------------|--------------|-----|
| DRAWN | 11-Dec-16 | TITLE | SIZE | DWG NO | REV |
| Ibrahim | | | | | |
| CHECKED | | | | | |
| QA | | | | | |
| MFG | | | | | |
| APPROVED | | | | | |
| Custom Size (mm) | | | TowerStructure_SideView | | |
| SCALE | 1 / 20 | | | SHEET 1 OF 1 | |

Dimensions

