West Virginia University
BENJAMIN M. STATLER COLLEGE OF
ENGINEERING AND MINERAL RESOURCES

West Virginia University

Drillbotics Phase I Design Report

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Abstract

Drilling system automation is the process of optimizing operating parameters by use of sensor input, control systems, and computer programming. This allows minimal human intervention, reduces safety risks, and maximizes efficiency while drilling. In order to accomplish this, a multidisciplinary team was recruited to design a fully autonomous drilling rig capable of adapting to changing downhole conditions. The proposed system is a top drive rig with a fluid circulating system controlled with artificial intelligence (AI) fed by a wide variety of sensors. The AI will use parameters collected via data mining to ensure safe and efficient operation. Real time data will be available through a local server allowing anyone with access credentials to view the data.

A rig comprised of t-slotted aluminum is envisioned with an attachable fluid circulating system and a movable instruments table to ensure mobility. A slew of soft and hard shutoffs including a remote shutdown, will be included for each system as well as a fuse for each electrical component. This is to ensure the safety of the team. The mechanical design was completed using Solidworks while AutoCad and Matlab were used to verify certain design aspects. The control system is comprised of the Intel Edison system on a chip which will operate all systems, and a Raspberry Pi 2 Model B to act as a local server.

The proposed rig will drill several different samples in all possible ranges under the theoretical operating limit, bounded by constraints such as the pump output and maximum weight on bit. A data mining process will evaluate the parameters and determine the data set to be used for the AI. The AI technique proposed is simulated annealing, a probabilistic metaheuristic used to determine acceptable global optimums. Simulated annealing is used to augment the parameters in order to avoid suboptimal combinations without resorting to preset options or using a brute force solution. This allows the rig to adapt and optimize parameters regardless of the material being drilled while mitigating risks downhole.

Team Bio

Dr. H. Ilkin Bilgesu is an Associate Professor with the Department of Petroleum and Natural Gas Engineering at West Virginia University. His areas of expertise are drilling and production engineering. He has been involved with rock and fluid properties related to drilling and production operations. His research covers topics related to safety and well control operations in drilling, subsurface integrity of wells and impact of fracturing on production from natural gas wells. His current research deals with modeling and prediction of in-situ stress conditions in subsurface wells drilled in shale formations and the well control operations in horizontal wellbores.

Zach Cox is a Petroleum Engineering Masters student and member of SPE and AADE; he previously pursued a dual degree in Mechanical and Aerospace Engineering with a minor in Nanosystems all at WVU. He is currently serving as a 2nd Lieutenant with the West Virginia Air National Guard as a Bioenvironmental Engineer having previously been an Avionics Technician. Zach is also an adjunct faculty member at Pierpont Community and Technical College where he teaches Hydraulics and Pneumatics courses.

Tawfik A. Elshehabi is currently a Ph.D. student at West Virginia University (WVU). He has B.S. and M.S. degrees in Petroleum and Natural Gas Engineering. His research areas of interest are real-time drilling optimization using artificial intelligence techniques and advanced well control. He has published three technical papers and made one poster presentation. He has participated in American Association of Drilling Engineers (AADE) 2015 National Technical Conference at the graduate level poster presentation, and finished second. He is a member of SPE and WVU Student Section of AADE.

Cody Smith is currently a student at West Virginia University pursuing his Master's Degree in Petroleum and Natural Gas Engineering. He completed his Bachelor's Degree in Mining Engineering at West Virginia University as well, with internships in Columbus, OH and Beckley, WV. During his

internship in Columbus, he worked with a Carbon Management group with carbon sequestration projects using abandoned gas wells. He is a member of the student chapters of AADE and SPE at WVU.

Rachel Richard is pursuing a B.S. degree in Petroleum and Natural Gas Engineering. She has worked in the oil and gas industry as a drilling engineer in Bakersfield, CA and a completions engineer in Covington, LA. She is the treasurer of the STEM sorority Alpha Omega Epsilon and involved in the student chapters of SPE, AADE, and the Society of Women Engineers. She also plays field hockey on the WVU field hockey team.

Safety

Safety is naturally the paramount concern when undertaking any project, regardless of the scope or scale considered. Due to the conditions faced and the environments to be encountered, special care must be taken with this project. Areas of heightened concern include: the buildup, electrical wiring and construction, operation, and maintenance. It is with this in mind that the following safety standards are put forth to be followed by the team at all times.

Buildup

During buildup, the primary concerns will be mechanical, pinch points, punctures, lacerations, cutting debris, and the like. In order to minimize risk, safety glasses will be required during any machining of the pieces to build the structure. Likewise, hearing protection will be required during these activities. Work gloves will be provided and general safety standards enforced. The build area will be kept off limits to those not involved in the project to avoid any additional hazards. Due to the light weight of the building material used, threat of injury is very low and very little machining will be necessary.

Electrical

All electrical systems must be set up, soldered, installed, and connected to power, with each step having its own safety concerns. Our group has two members with extensive experience with electrical components who will guide the other members in their tasks to ensure safety. Upon the setup of each system, any capacitors will be discharged and all power disconnected. When working on the systems no power will be applied and each team member must wear a grounding strap. While soldering, safety glasses will be required and a vacuum system will be used to remove harmful fumes. Systems will be installed separately on the main instrument table before being connected to any other system. Individual component testing will be verified using an oscilloscope and multimeter to avoid damage to other systems and reduce risk to the individual. Once tested, all components will be assembled and each unit tested again to ensure proper operation. As an extra safe guard, every connection from the power

source will house its own fuse to avoid any fire hazard due to an overloaded circuit. While the power supplies contain a fuse, this governs total power used whereas individual fuses allow for overcurrent protection in every component. When possible, off-the-shelf components will be used to ensure safety and ease of operation. All connections will be properly terminated, insulated, and/or connected prior to use and all voltages and amperages will be thoroughly documented. High voltage components will be isolated from other components and the user to avoid any possibility of accidental electric shock. All systems will connect to ground via the mains AC source to ensure proper operation and protection. Hard and soft shutoffs as well as a remote shutdown will be built in to allow for any level of risk mitigation.

Operation

During operation, few risks are expected as the automated protocol keeps the individual away from most danger. However, supervision of the rig will be mandatory during operation in case emergency shutdown is required. Prior to testing a safety briefing will be held for the team and attendance will be mandatory. A fire extinguisher will be available on-site should it be needed. All electrical components will be required to be enclosed in their designated areas prior to operation to avoid any water hazard. Safety glasses will be required while observing the unit, and outside personnel will not be allowed to freely traverse the site. Hearing protection will be provided to the members observing the unit.

On-site storage and maintenance

In line with professional safety standards, safety data sheets will be available on-site to document all chemicals used. Furthermore, documentation of the electrical systems mentioned previously will remain with the rig. A lock out tag out system will also be in place whenever maintenance is being performed. Disposal of all waste will be recorded and kept with the rig, if chemicals are used they will be documented and all waste will be disposed of in accordance with local regulations. All activities will adhere to university, state, and federal regulations to ensure safe and responsible operation.

Mobility

The rigs' design includes a folding table to accommodate the electrical components, as well as removable supply and return tanks for circulating fluid. In order to move the rig, the table will be folded up and secured to the rig, and the circulating fluid tanks must be removed. Once the rig is ready for transportation, a set of wheels and a built in handle will allow for a single person to tilt and wheel the rig like a moving dolly. This will allow the normally stationary rig to be angled to fit through doorways, and the construction is small enough to allow easy movement in and around a most buildings. The aluminum construction will ensure a lightweight frame while still providing enough strength for the structure to be moved around regularly, which will be necessary when moving the rig between the storage and testing locations. The total rig height is just over 8 ft., allowing easy ingress and egress through standard doorways, with only a slight tilt needed. In the event that the structure is still too big, the modular construction allows for easy removal of many parts, allowing the rig to be disassembled and reassembled in a very short period of time. The electrical and pump components can also be removed easily via quick-connects, meaning they can be safely stored and transported with the rig.

Design Considerations/Lessons Learned

Currently, rig operation is a complex routine requiring coordination from all involved in order to accomplish. As all operations are dependent on the operator, efficiency and safety can vary widely on the same rig. In addition, the data available may be too substantial for a single individual to comprehend and the result could be dangerous. However, trained individuals can be invaluable and provide relief from some devastating conditions faced downhole. These are the workers whom are able to detect problems before they arise and navigate difficult drilling conditions with little knowledge of the formation.

Current operations have the advantage of trained personnel and a readily available source of help should the need arise. This is due to the workers onsite, both those working and those off shift who can offer guidance and assistance. There is also a robust monitoring system employed in present day drilling operations allowing an operator a quick and easy source of information. The number of sensors and downhole tools can vary widely, and the data available can be used to make major decisions when utilized by the driller.

While current operations have the advantage of more personnel and potentially more assistance onsite, automation provides many possible benefits over the standard operations. For instance, the amount of data provided to the driller may be ignored or not fully utilized, resulting in sub optimal performance. Changes to the drilling parameters based on the data may be slow or even nonexistent whereas all data will be monitored and used by an automated controller. Lastly, the number of sensors and the impact of the data can more efficiently be used by an onboard computer which is always seeking out the best operating solution while simultaneously operating within a safe criteria. This means fewer works which would mean fewer accidents, less miscalculation, and safer drilling in general.

Thus far, all design has been student led with no external involvement and only the supervision of the faculty advisor. The intention is that this project be completed entirely by the team with no outside involvement.

Design of the rig includes not only current examples from industry but also the limitations based on readily available components. One example encountered is the difficulty in finding pumps that are sufficiently cheap but have high flow and pressure. Often pumps considered could only reach 125 psi. with flow rates hovering around 4 gpm. Motor selection was dictated by torque and power draw as the competition power limitation required a conservative design.

Mechanical design was refined often with many considerations ultimately being done away with. This was to ensure a mobile and safe operating platform that could be adapted to future competitions as well as general lab use. A modular design was considered for this reason, and component mounting is done in a way that will allow them to be moved or removed easily. The traveling system for the drill motor includes a 3D printed frame traveling on 3 linear bearings. While two bearings were initially considered, the resulting torque from an uneven layer or travel of the bit could cause the block to misalign. This would stop the block from traveling at all if only 2 bearing are used. However, by using 3 bearings, the system is more rigid and will allow for less deflection in any plane.

Potential materials were broadly discussed and pros and cons revisited regularly. Although using steel would create a stronger, permanent structure, the weight and size was an issue. In addition, as no member of the team is particularly adept at welding, a simpler solution was preferred. Even wood was considered at one point due to the ease of machining but was discarded due to multiple reasons. A light weight material which could be easily adapted and changed should the need arise was sought after. T-slotted aluminum framing was chosen and is mentioned in more detail in the mechanical design section of this report.

Control system selection was based partially on price, but also on the consideration of true autonomy. In this spirit it was considered that a traditional computer would allow undesired access to the program. Additionally, a full computer would only add cost and power draw whereas microcontrollers and SoCs (system on a chip) are incredibly cheap and relatively powerful.

While designing the rig lessons learned include:

- Fuse protection within power supplies is insufficient and individual component fuses will be utilized.
- The traveling system must be robust enough to handle and mitigate bit traveling.
- Component selection must be based on available products, the ideal properties may not be available.
- Multidisciplinary teams are essential due to the complicated nature of this project.
- Safety cannot be disregarded due to the multiple hazards, high voltage/current, torque, and dangers involved in a project of this scope and scale.

Mechanical Design, Functionality, and Versatility

Design and Construction Challenges

When designing and building a structure of any kind, there are going to be a significant amount of changes and adjustments that are necessary, even with a very detailed schematic and dedicated research. To that end, it is necessary for the participants in this competition to have building materials that allow for some flexibility, while still maintaining durability. Here are some of the challenges that the team has discussed, and our design solutions to those challenges.

Utilizing Effective Construction Materials

One of the most important components in the drill rig design is the material that is being used to construct the derrick and supporting structures. Several materials were evaluated based on their weight, cost, strength and versatility. Potential choices were wood, steel, or t-slotted aluminum extrusions. Wood was discounted because of its weight and the structural stability lost if changes were made and pieces were reused. Steel was also eliminated based on its weight and the lack of versatility in welding the frame and not being able to easily change designs. By comparison, t-slotted aluminum is very lightweight for its strength and relatively cheap, which allows for some degree of over designing, and very easy to disassemble in order to change configurations. The cost and ease of use for the t-slotted aluminum extrusions, make it an ideal material for the design of the support structures as well as the derrick.

The primary configurations of the t-slotted aluminum being used in the design are the 1-inch by 1-inch, or “single”, and the 1-inch by 2-inch, or “double”. Because of the relatively light weight of the motor and overhead components of the rig, it was decided that most of the frame would suffice being constructed with singles. These were used, along with hand-brake hinges, to design a table that will be attached to the side of the rig and can be folded up for ease of transportation. Also, two 6-inch aluminum L-brackets will be attached at the bottom of the rig, opposite and adjacent the table, on

which will be placed 55 gallon plastic drums that will serve as drilling fluid tanks. This should reduce some of the projected movement due to vibration in the rig.

Maintaining Straight and Measurable Traveling Block Movement

Another critical component to the drilling process is making sure that the traveling block and the drill stem travel smoothly and for this competition, straight up and down. Because the strongest structural shape is a triangle, three upright cylindrical guide rails were built into the derrick to control the horizontal movement of the traveling block. The drive motor is being housed in a motor mount that is being 3D printed in house. This motor mount will be attached to a chain from the top, which will loop over a large sprocket directly above the drill stem. The chain will then run to a much smaller sprocket attached to our drive motor, which will give us a significant mechanical advantage.

In addition to making sure the motion of the traveling block is smooth and vertical, it is important for the actual automation of this rig that the movement is able to be measured precisely. The drive motor that has been chosen, along with the proposed gear arrangement, will ensure that any movement by the drill stem is accurately measured. We have proposed ordering our lift motor from McMaster-Carr as well. The lift motor is a position control motor so that the lifting and lowering of the drill string can be accurately controlled and measured. The lift motor that has been chosen is a Position Control DC Motor, class NEMA 34. The maximum RPM is 720, and the motor has an operating torque of 70 in.-oz. While the RPM is well above anything that would be needed for this application, this motor provides the largest torque in its class, which will be needed to lift the drive motor, drive motor mount, and drill string. In order to aid the lift motor in this endeavor, the chain that will lift the drill string will be weighted on the loose end to counterbalance the weight of the assembly.

Drill Motor and Pump Considerations

Calculations:

In order to pick an appropriate drill motor, calculations were performed to determine theoretical maximum shear. This was approached in several ways: calculating maximum shear stress based only on shear yield, using von Mises to calculate a safety factor greater than 1.1, and validating the results by hand. To calculate the maximum allowable shear using maximum shear yield the following equation was used:

$$T_{max} = \frac{\pi}{16} * \sigma_{max} *= \frac{\pi}{16} * (14000) * \frac{0.375^4 - 0.343^4}{0.375} = 43.5\ inlb$$

Next, a program was written in Matlab to test all possible combinations of loading to develop a theoretical operating envelope. This was then setup to test only for shear stress using von Mises criteria to calculate the Tmax to give a factor of safety of 1.1. This yielded a Tmax of 30.9 in lb., considerably less than the 39.5 in.lb. from the first equation after the safety factor was applied. This can be attributed to using an oversimplified equation that does not take other material mechanics into consideration. The calculations and results of the combined loading are shown below. In Figure 2, FOS is only shown for the maximum torque allowed considering the other values. The most prominent characteristic of the graph is the general decrease of allowable torque as pressure increases. In addition as pressure increases significantly, a compressional load is necessary to counter the axial stress caused by the internal pressure. The values chosen are bounded by the average maximum torque based on the above equations, maximum pressure under combined loading, and the allowable WOB as described in the contest rules.

von Mises equations:

For 2D von Mises with the tubular, the outside face is considered under combined loading. Here the compression and shear are considered directly. Pressure however must be replaced by axial and hoop stress to be applied. Using thin wall approximations, the following equations are used:

$$\sigma_{axial} = \frac{P * r_m}{2 * t}$$

$$\sigma_{hoop} = \frac{P * r_m}{t}$$

Where P is the internal pressure of the drill string, r_m is the mean radius, and t the wall thickness of the tubular. Next compression and shear are considered using the equations below:

$$\sigma_{comp} = F/A_{alum}$$

$$\tau_m = \frac{T * r}{J}$$

Here F is the compressional force applied, A_{alum} is the cross sectional area of the aluminum tubing, T is the torque applied, r is the radius being examined, and J is the polar moment of inertia. These equations will all be considered together in order to determine the von Mises stress and corresponding safety factor. Figure 1 shows the forces acting together on an element, it can be seen that the compressional force opposes the axial force and the torque is the only component of shear stress.

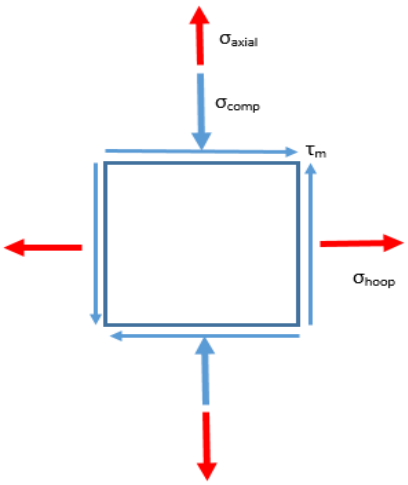

Figure 1 Combined loading of drillstring, pressure forces shown in red

These forces are resolved into the principal stresses σ_1 and σ_2 which are in turn used to find von Mises stress σ_c and the safety factor below:

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_m^2}$$

$$\sigma_c = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}$$

$$n = \frac{S_y}{\sigma_c}$$

This process can be used with any combination of forces to determine the factor of safety, however for the purposes of choosing a drill motor only torque will be considered. This will guarantee that the drill motor is not a weak point in the design. The Matlab program was used to test all values within the operating range dictated by the above parameters and competition restrictions. The following equations show the maximum torque value (30.9 in.lb) found with the program and validate the outcome.

Considering only torque:

$$J = \frac{\pi}{2}\left(r_{out}^4 - r_{in}^4\right) = \frac{\pi}{2}(0.1875^4 - 0.1715^4) = 0.0005826\ in.^4$$

$$\tau_{max} = \frac{T * r_{out}}{J} = \frac{30.9\ inlb\ *\ 0.1875\ in}{0.0005826\ in^4} = 9944.64\ psi$$

Since only torque is considered, it is known that the principal stresses are the same as the shear. Only the second principal stress is negative while the first remains positive.

$$\sigma_1 = 9944.64\ psi$$

$$\sigma_2 = -9944.64\ psi$$

$$\sigma_c = (\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2)^{0.5} = \left(9944.64^2 + (-9944.64)^2 - (-9944.64 * 9944.64)\right)^{0.5} = 17224.62\ psi$$

Yield stress is taken as 19000 psi as per the material properties available from the tubing manufacturer.

$$n = \frac{S_y}{\sigma_c} = \frac{19000}{17224.62} = 1.10$$

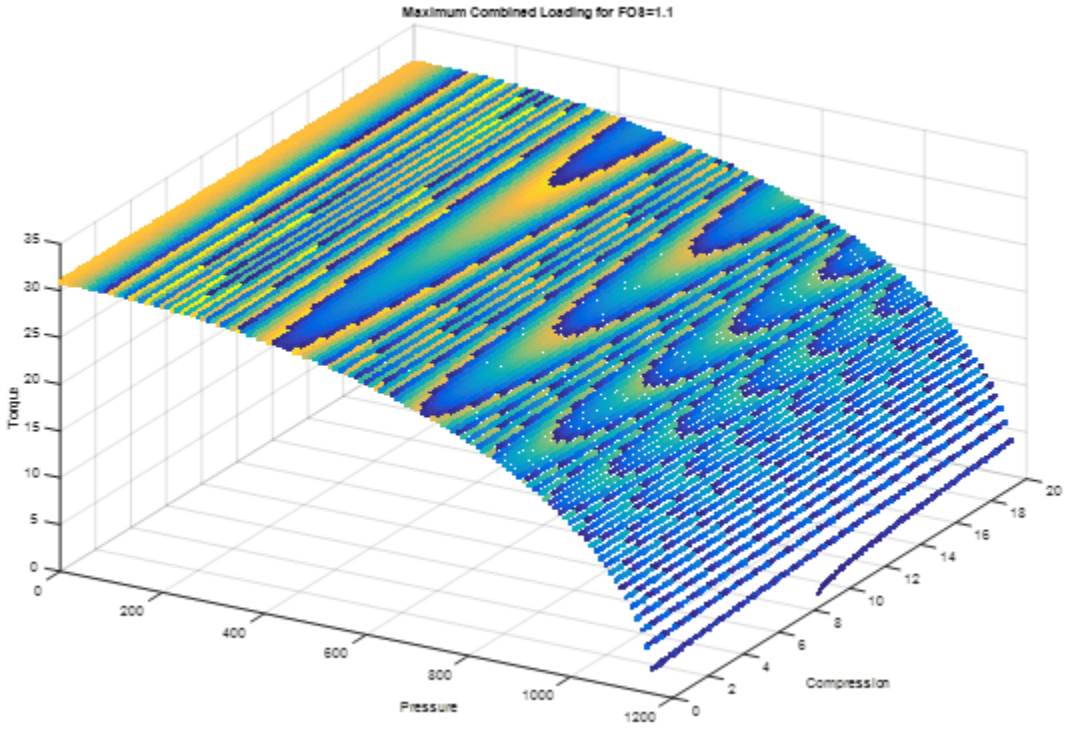

Figure 2 Operating envelop for FOS=1.1

Several different drill motors were evaluated for use in the drill rig. Because the bit is a PDC bit rather than a roller-cone bit, more consideration was placed on RPM than Weight on Bit. A Right-angle DC Gearmotor from McMaster-Carr has been selected due to the wide operating RPM and high torque, at a very low overall horsepower. Due to the analysis of the drill stem, which in this case is a fairly light aluminum, it was decided that our operating torque should remain under 30 in.-lbs. The specifications for the proposed drill motor are 1/8 Horsepower with 25 in.lb. of torque at 237 rpm, a range of 0-250 rpm, and stall torque of 50 in.-lbs. The controller chosen can safely and easily limit the current delivered and therefore the torque of the motor ensuring safe operation. The horsepower limitation for this design is 2.5 hp for all systems, and this also played a role in our motor selections.

Another important factor in the design of a drilling rig is the fluid circulation system. It was determined from the above program that the maximum allowable internal pressure of the tubing was

approximately 1,200 psi when a von Mises factor of safety of 1.1 was used, and the appropriate flow rate to remove cuttings from the hole was between 4 and 8 gallons per minute. To meet these criteria, a pump was chosen that had a maximum flow rate of 7 gpm and a maximum output pressure of 125 psi.

In this design a water based mud polymer system is considered with mud density 8.6 ppg, plastic viscosity 10 cp and yield point of 14 lbs/100 sq ft. The pump can operate between 4.2 and 4.8 gallons/minute with a max pressure of 125 psi. For the hydraulics design power-law model is used to check adequate mud flow performance. The following equations were used to verify the pump design:

$$Annular\ velocity\ =\ 24.5\ *\frac{Q}{\left(D_h^2-D_p^2\right)}\ \ ft/min$$

$$Pressure\ drop\ at\ bit\ =\frac{(\rho*Q^2)}{10858*TFA^2}\ psi$$

$$Total\ flow\ area\ (TFA)\ =\frac{\pi}{4}*\Sigma(D_n^2/32)\ in^2$$

$$Hydraulic\ horsepower\ =\ \frac{P*Q}{1714}$$

$$Jet\ velocity\ =\ \frac{417.2*Q}{\Sigma(D_n^2/32)}\ ft/sec$$

$$Impact\ force\ =\ \frac{V_j*\rho*Q}{1930}\ lb_f$$

$$Hydraulic\ lift\ force\ =\ APL*(A_{bit}-A_{nozzle})\ \ lb_f$$

$$V_s=0.45\left(\frac{PV}{MW*D_p}\right)\left[\sqrt{\frac{36800*D_p}{\left(\left(\frac{PV}{MW*D_p}\right)^2\right)}*\left(\frac{DenP}{MW}-1\right)}-1\right]$$

Here the cutting slip velocity (Vs) is in ft./min, APL is annulus pressure loss in psi., DenP is cutting density in ppg, Dh is hole diameter in inches, Dn is nozzle diameter in inches, Dp is the drillpipe outside diameter in inches, MW is the mud weight in ppg, P is pressure in psi., PV is plastic viscosity in

centipoise, Q is flow rate in gallons per minute (gpm), TFA is total flow are in square inches, and Vj is jet velocity in ft./sec. The bit has 2 nozzles with the size of 2.35 mm (0.0925 in) and the total flow area is 0.0134 in^2.

At the minimum flow rate of 4.2 gpm the annular velocity is 91 ft./min. The pressure loss at the bit is 73 psi and total pump pressure required is 100 psi with power consumption of ¼ hp. The jet velocity is 97.7 ft./sec which creates 1.83 lb. impact force on the bottom of the well. At that rate the weight-on-bit is reduced by hydraulic lift force of 4.9 lb.

As the pump maximum pressure is 125 psi, the max flow rate is 4.7 gpm. The annular velocity is 105 ft./min. The pressure loss at the bit is 92 psi and total pump pressure required is 125 psi with power consumption of 0.34 hp. The jet velocity is 109.3 ft./sec which creates 2.29 lb. impact force on the bottom of the well. At that rate the weight-on-bit is reduced by hydraulic lift force of 5.9 lb.

A hole cleaning study was considered at minimum and maximum pump flow rates (4.2 and 4.7 gpm). At 4.2 gpm a Cutting Carrying Index CCI of 1.04 can be achieved for good hole cleaning but the minimum PV and YP are 10 and 14. Also, cutting slip velocity is 45 ft./min and net cutting rise velocity is (91-45) 46 ft./min. At 4.7 gpm a Cutting Carrying Index CCI of 1.21 can be achieved for good hole cleaning. Cutting slip velocity is 45 ft./min and net cutting rise velocity is (105-45) 60 ft./min.

Proposed Design

Once all the mechanical parameters were determined and the construction material chosen, the physical design of the system began. Shown below in Figure 3 is a bare 3D representation of the proposed rig. Here the drill motor can be seen protruding from the travelling assembly right above the stem for the water swivel. The lift motor is at the top of the structure directly coupled to the shaft with the smaller sprocket. The mount for the lift motor and the drill motor are both to be 3D printed, this allowed for them to be designed on the fly. The instrument will house all electronics in an acrylic box carefully vented to allow airflow but protect from any errant fluid. The tanks for the circulating system are shown and will be removed when storing or transporting the structure. The pump itself will mount underneath the instrument table further isolating the electrical components from any potential spills. While not shown, the lifting mechanism will use a chain with a counter weight which will travel between the drilling structure and the table. This is to reduce the load on the motor and ensure that the drillstring will not crash down in the event of a shutdown or power failure.

Total rig height is 7’ 2” with a height above sample of 5’ 8” a width of 18” and a total length of 8’ 1.89” with the table folded down and barrels attached. Transport dimensions are height of just over 7’, width of 30.58”, and a length of 2’. The structure is shown folded up in Figure 4 with the casters clearly visible. The dimensions were chosen to easily accommodate a sample, allow for easy storage and mobility, provide a structurally sound platform for drilling, and allow for easy removal or addition of components.

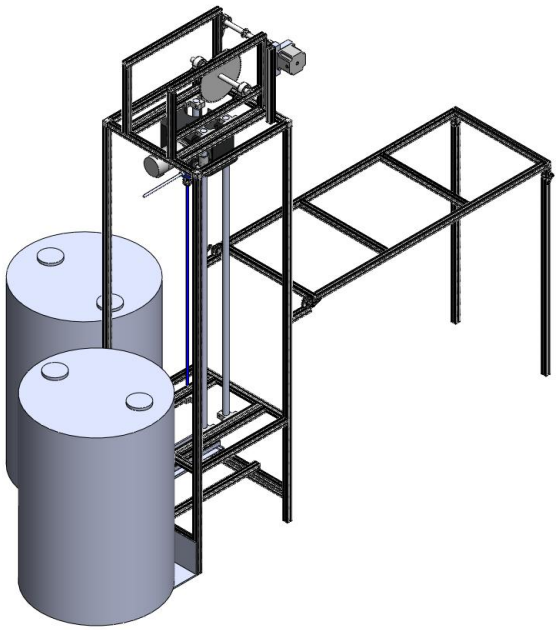

Figure 3 Full layout 3D rig model

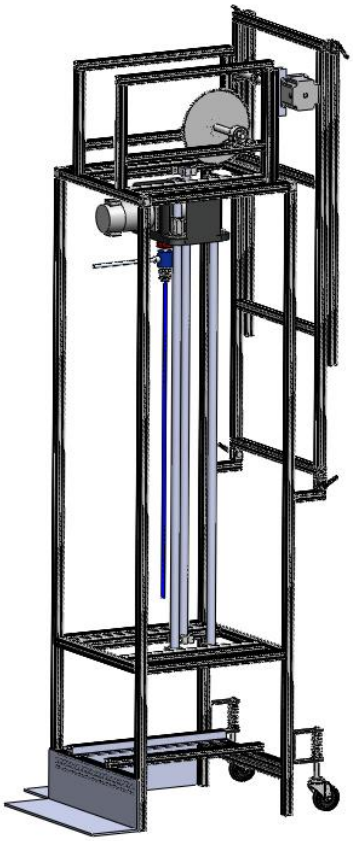

Figure 4 Folded 3D rig model

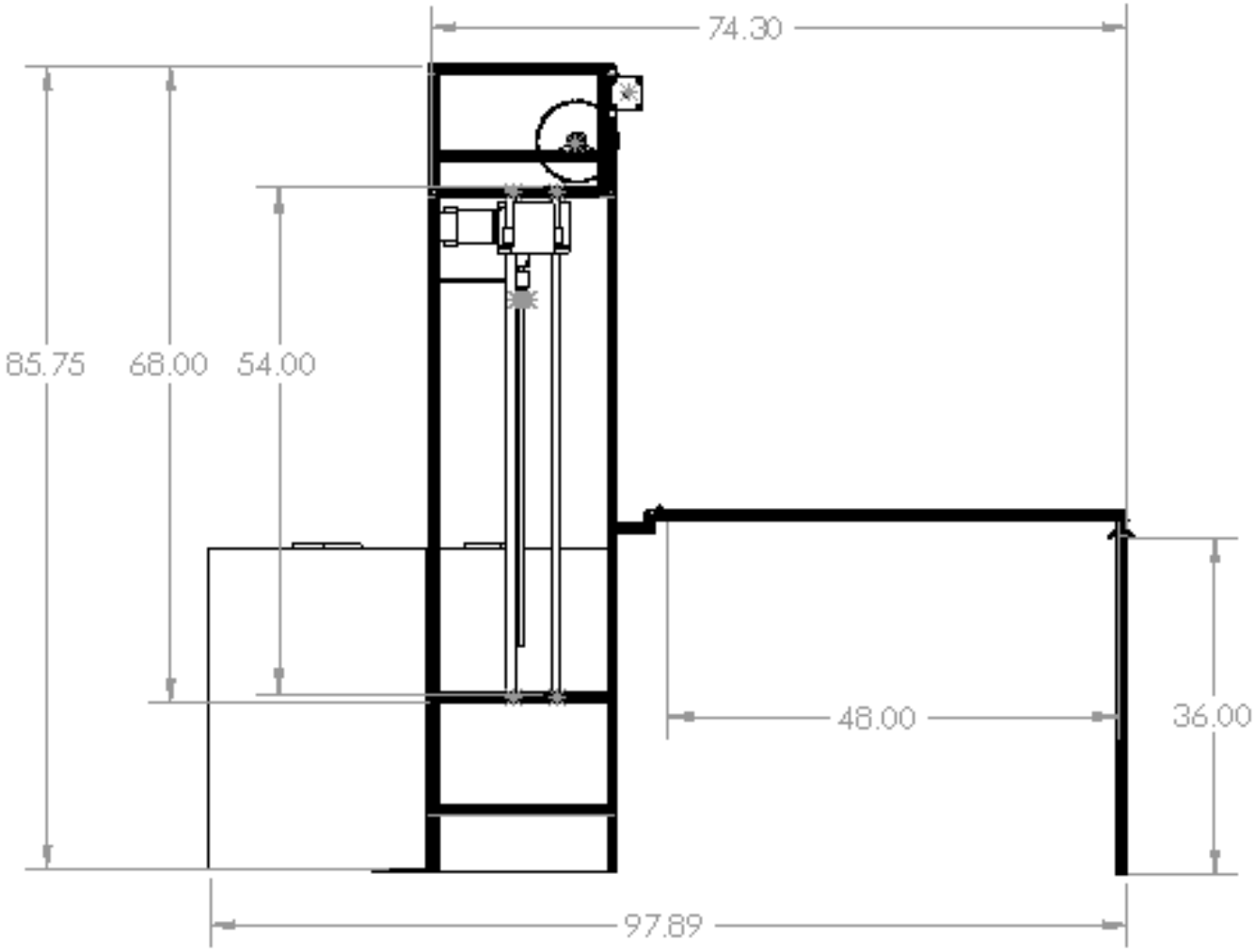

Figure 5 Engineering drawing of the rig, front side

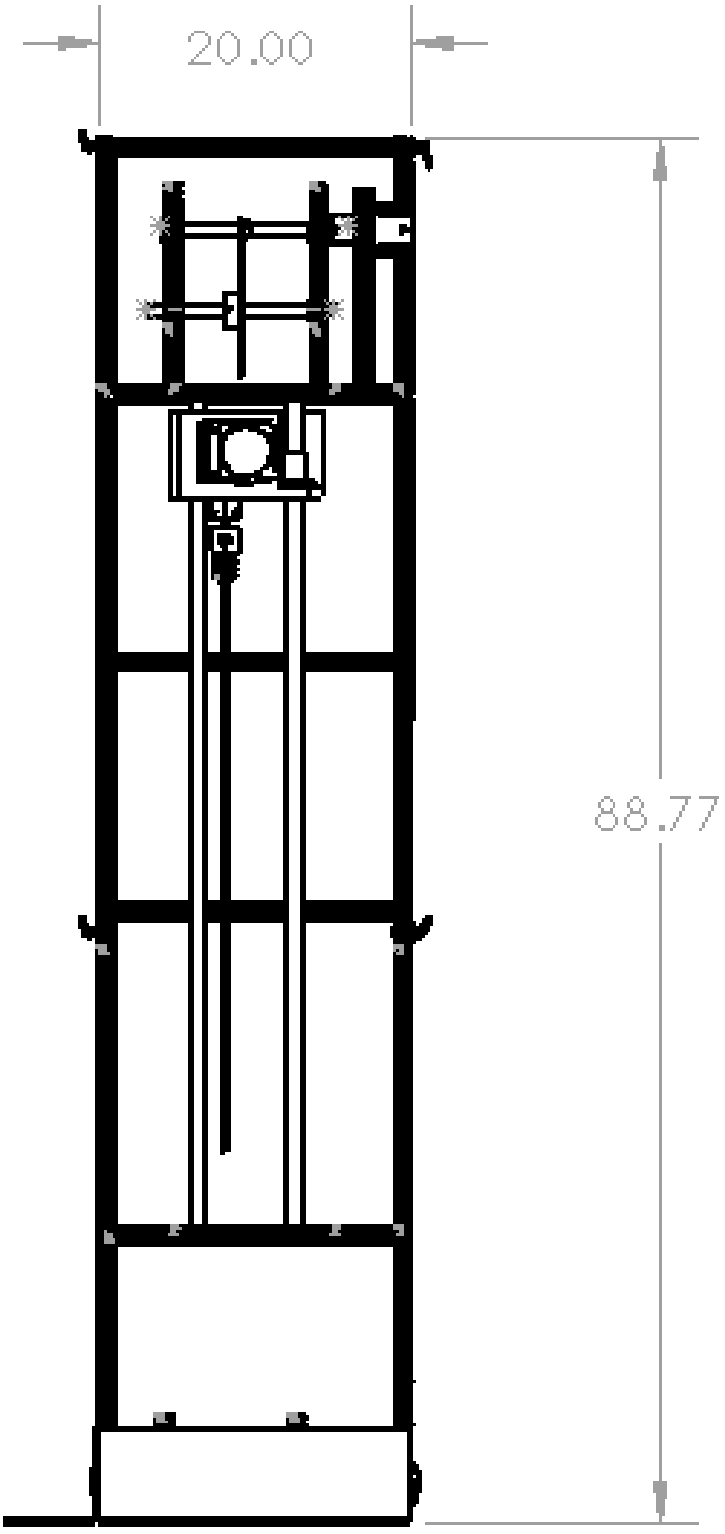

Figure 6 Engineering drawing of the rig, table up tanks removed

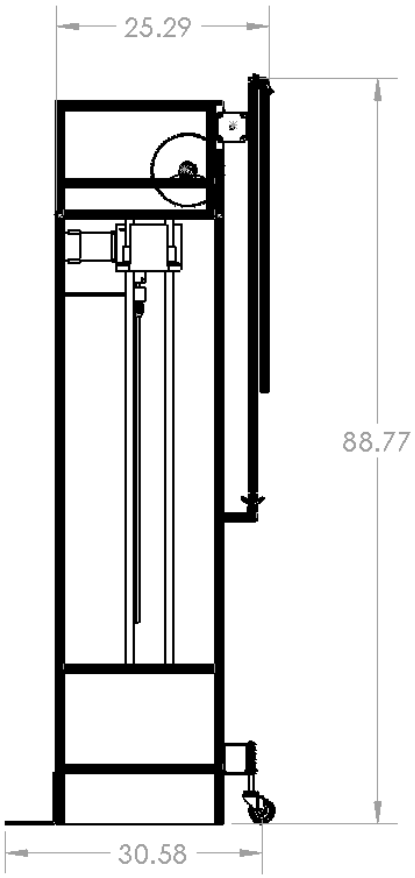

Figure 7 engineering drawing table up, side view

Simulation/Model/Algorithm

Drilling performance can be analyzed in terms of how fast it drill (rate of penetration-ROP) and how much it cost (cost per foot-CPF). As shown in equation 1, the higher the ROP and drilled footage, the lower CPF and better drilling efficiency. Furthermore, drilling efficiency is measured by mechanical specific energy (MSE) that can be defined as amount of energy required to remove a unit volume of rock. As shown in equation 2 any change in drilling parameters can be detected by monitoring MSE. Minimizing MSE by optimizing controllable parameters results in maximizing ROP.

$$CPF = \frac{C_{bit} + C_r * (t_r + t_r + t_o)}{\Delta D}$$

Here the cost per foot is calculated in USD per ft. and is a function of bit cost (C_{bit}), rotating time (t_r), trip and connection time (t_t), other time (t_o), and total footage drilled (ΔD) with time reported in hours.

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

The parameters used are weight on bit in pounds (WOB), area of the wellbore in square inches (A), torque inlbs (T), and rate of penetration in/rev.

Controllable drilling parameters are weight-on-bit (WOB), rotational speed in revolutions-per-minute (RPM) and mud flow rate in gallons-per-minute (gpm). Monitoring parameters are torque, pump pressure, hole deviation, string vibration, mechanical specific energy (MSE), and cost-per-foot CPF. Therefore, the objective of drilling optimization is maximizing ROP, with minimizing MSE and CPF. Also, torque, deviation and vibration should be limited to a safe operational range. Practically, the selection of optimum drilling parameters (WOB and RPM) can be achieved by performing the Drill-off Test (DOT). It

consist of applying a large weight to the bit and then lock the brake and monitor WOB decrease with time. This test can be repeated at different RPM values and optimum combination can be selected.

In this project an artificial intelligence protocol will be applied to real-time data and previously collected rig testing data. This proposed optimization algorithm is simulated annealing (SA) that can be defined as a generic probabilistic metaheuristic for searching large discrete spaces to find the global optimum. SA is analogous to the annealing process in physical chemistry, when liquid metals heated and then left to cool down into a steady, organized state. The algorithm goal is to bring the SA temperature from an arbitrary initial state to the minimum energy state. The major advantage over other optimizations techniques is the ability to avoid becoming trapped at local optimum by doing random jumps as shown in Figure 8 below.

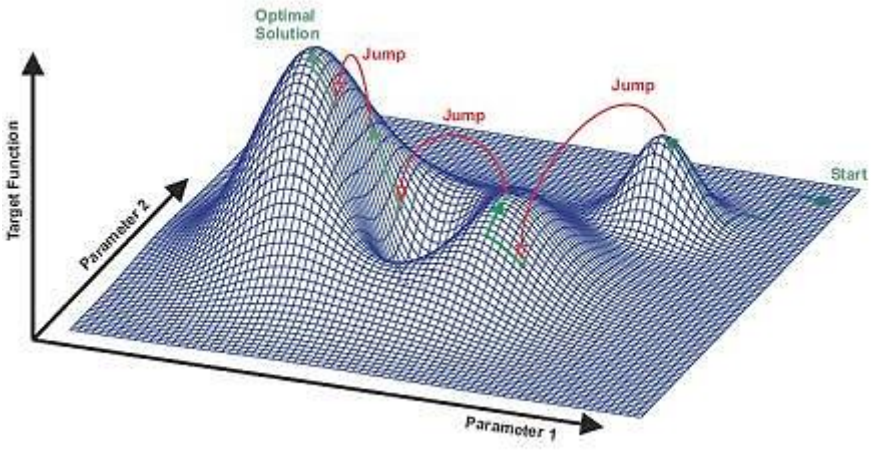

Figure 8 Simulated annealing example

An objective function C(x) can be defined for the solution space X which contains feasible solutions that fulfil all the constraints. At each state (x) the algorithm search the neighborhood for optimum solution. The decision of whether to move to a next state (x_{i+1}) or not depends on the values of C(x) and C(x_{i+1}). This decision allows the acceptance of some non-

improving solution just to escape local optimum trap based on acceptance probability function equation 3.

$$Probability\ (accept\ x_{i+1}) = \min(1, \frac{e^{C(x_{i+1})-C(x)}}{t})$$

Where ***t*** is the temperature control parameter that governors the radius of the search. Convergence to global optimum is guaranteed if ***t*** approaches 0.

The SA can be bound to operate only within the safe limits determined by onsite testing and the theoretical operating envelope. Although this means that the rig must try different combinations and view the results, this can be performed quickly. Data mining will be performed on many samples to be drilled under different variables and the data analyzed to determine which combinations will work best. This will be done with an automated program which will drill a preset depth to allow for the parameters to stabilize. This means the rig is not simply optimized for a homogenous rock or an average of rocks, but rather it will always seek out the best possible combination of variables. This combination of software allows for a highly adaptable rig which does not operate on presets for ideal rock types or operate based on a best fit constant. This is necessary as strict presets allow for no change with downhole conditions and cannot mitigate additional risks. The incorporation of AI in the system allows for the rig to continuously improve and avoid the shortfall of preset automation techniques.

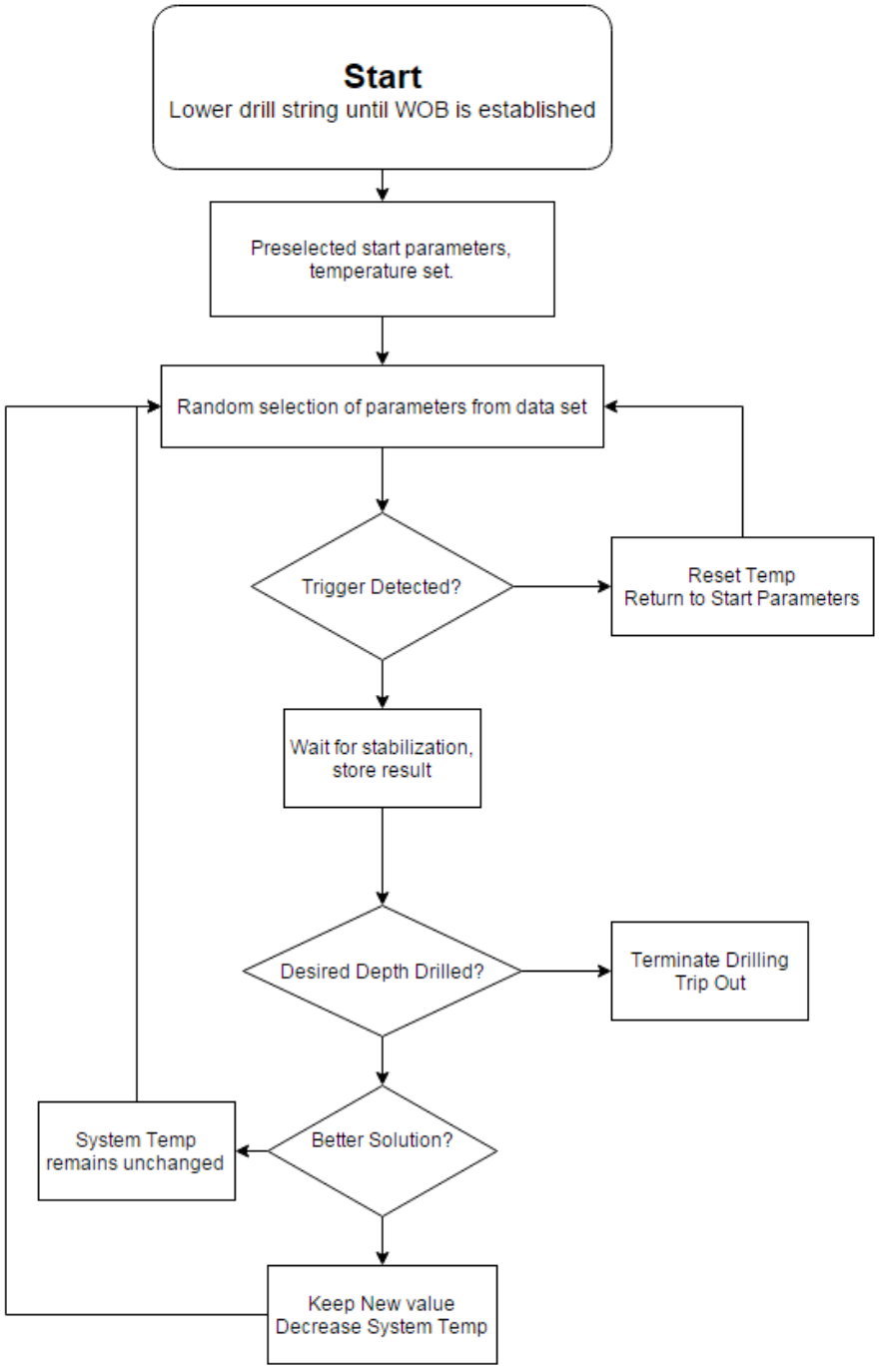

Figure 9 Simulated annealing flowchart

Simulated annealing (SA) works by first picking random values (all within the range dependent on the data mining) and finding the resulting solution. Here the program would

select values for WOB, RPM, torque, and fluid flow, apply them and read the ROP for example. Next the program would select another random set of values, if the ROP is higher the temperature of the system decreases. The temperature of the system correlates with how far apart the variables that are picked. When a higher ROP is found, the temperature lowers, when ROP continues to decrease the temperature restricts the values to within a smaller and smaller range around the global optimum. The random nature of the variable picking ensures that the program does not get stuck in local maximums and is able to react to any rock type without prior information dictating its behavior. When the system sensors detect a change (trigger), or if any of the calculated parameters show a significant deviation the temperature of the system can be reset. This means that if a new layer is encountered the program will automatically begin to optimize for that new layer. In addition, if the wellbore begins to deviate, the program can reset to counteract any misdirection and keep the bit from traveling based on sensor input.

Control Scheme

The proposed rig design will be controlled by an independent microcontroller which will receive input from all sensors, apply the control algorithm, and then wirelessly transmit the data to a local server. The server will store the sensor and optimization data, and output pertinent data to any connected device through a standard wireless router. In this way, anyone with authorization on the site can connect to the server to see real time data and access data history with any wireless device.

Data acquisition, processing, and distribution will be handled by an Intel Edison system on a chip. This system allows for full use of GPIO (General-purpose input/output) pins to handle all sensors and controls while providing wireless capabilities via onboard Wi-Fi and Bluetooth antennas. The system is composed of two Intel Atom Silvermont cores running at 500 MHz and one Intel Quark core at 100 MHz. The slower core is used exclusively to handle microcontroller tasks associated with the GPIOs. This system can be programmed with multiple standard languages and allows for the system to run with no external input aside from a start signal. This allows for massive cost savings as a normal computer is not fully utilized and requires a technician to properly access and start a program. Data storage and visualization will be handled by a Raspberry Pi 2 Model B single-board computer acting as a local server. As with the Intel Edison, the Raspberry Pi can easily be programmed in many languages and with its 900MHz quad-core ARM Cortex-A7 processor, it can handle the demands of outputting data to many devices. The Pi will interface with a standard Wi-Fi router to allow access to the data in real time as well as access to past data.

This system relies on a wide array of sensors to provide data relating to all the systems involved in the rig. This data will be analyzed and used to ensure safe, reliable, and optimal performance. In order to input all the required data from the sensors to the Intel Edison, external multiplexers are used to multiply the number of inputs available. A block diagram is shown below detailing the connections from the Edison to the various sensors. A detailed description of the elements in the diagram follows.

Power for the system must provide a wide range of operating voltages and allow for sufficient amperage in order to power all sensors and devices. The pump is powered via mains AC and requires no additional power structure, although a variable frequency device (VFD) will be used in order to manipulate the flow rate of the pump. The drill motor chosen requires 90 VDC which will require a simple circuit to rectify mains voltage and provide a near stable DC output, a variation of this circuit is shown in Figure 10. All remaining components will be powered by an ATX power supply with outputs of +12V, +5V, 3.3V, -12V, and -5V DC. The ATX power supply guarantees a smooth DC output with sufficient current to power many sensors. Moreover, the output voltages may be combined in order to provide power to devices requiring 10V, 24V, and in the case of the stepper motor 48V DC. This factor combined with the cost, and safety of an off the shelf power supply make the ATX supply a better choice than single voltage output supplies.

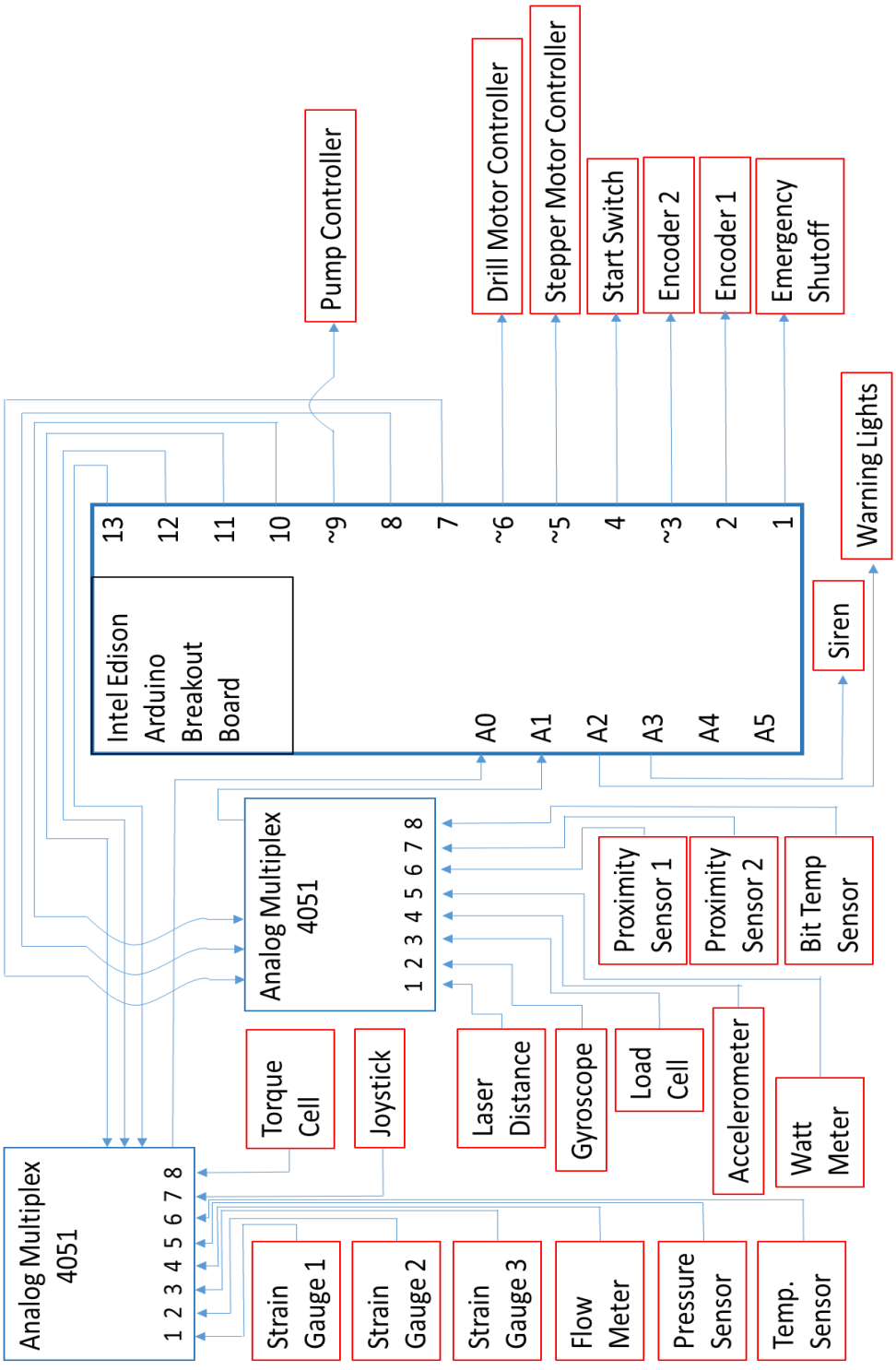

Figure 10 Wiring diagram for the microcontroller

Sensors

The majority of sensors and drivers are listed below with a brief description and cost. In addition to these sensors, two encoders will be made and placed above and below the slip clutch. These will provide a direct measurement of rpm but will also indicate if the clutch is slipping, allowing for the program to change speeds or WOB. Many of the sensors provide feedback which will be used to signal the program that the wellbore conditions are changing (such as increased vibrations) and do not directly change WOB, RPM, or circulation. This is to ensure a vertical well with as little deviation as possible while maintaining high ROP. Other sensors have no input related to drilling, instead the act only to sustain the system. In addition to the sensors shown, there is also a single switch to activate the system and pause drilling, one to perform a soft stop, and a hard stop in case of emergencies. These will be used with an annunciator system comprised of LED strips and a small siren which will provide a visual status of the system at all times and an auditory alert when changes.

A list of all proposed sensors and controllers follows with a brief explanation of their purpose as well as price and source if determined. This is not to be considered an exhaustive list, but rather all options considered in Phase I.

Strain Gauges

Cost $110.00 for 5

Source: Omega.com (http://www.omega.com/pptst/SGD_3-ELEMENT45-90.html)

Three strain gauges (3-element strain rosette) are to be attached to the drill string to allow for constant stress analysis which will govern the control of the torque, WOB, rpm, and fluid pressure applied. These

gauges will connect via a slip ring to the Edison to provide strain data aligned with 0, 45 and 90 degree positions on the pipe surface.

Flow meter

Cost $100.00

Source: jmesales.com (http://www.jmesales.com/catalog/productinfo.aspx?id=13444&cid=5902&skuid=PIF0048000A&gclid=CLTJ8e3lpMkCFQv3Hwod5u4ElA)

A flow meter will measure the flow from the pump in order to calculate cutting removal and jet force on the nozzle. This inline sensor has an operating rang of 0.26 to 7.9 gpm, well within the expected range to be used.

Pressure Transducer

Cost $225.00

Source: omega.com (http://www.omega.com/pptst/PX309-5V.html)

A pressure transducer will be located in line with the flow meter to monitor fluid pressure going into the drill string; rated pressure range from 1 to 10,000 psi.

Temperature Sensor

Cost $ 1.59

Source: jameco.com (LM35DZ) (http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_155740_-1)

A temperature probe will be used to monitor bit temperature during the drilling process to ensure proper bit cooling. These sensors range from 0 to 100°C with an accuracy of +/-0.6°C.

Torque cell

Placed in line with the drill string and drill motor to provide feedback regarding real torque applied.

Position Switch

Cost $ 1.59

Source: jameco.com

(http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_317287_-1)

One of the only user controllable inputs in the system, the joystick will allow for the raising and lowering of the assembly manually prior to the start of drilling.

Linear Displacement Sensor

Used in conjunction with the stepper lift motor to ensure precise depth information.

Gyroscope

Cost $1.65

Source: digikey.com (http://www.digikey.com/product-detail/en/L3GD20HTR/497-13931-2-ND/4357643)

Used in the BHA to provide feedback regarding the verticality of the well and deviation severity.

Load cell

Cost $ 175

Source: Omega (http://www.omega.com/pptst/LCEB.html)

Placed between the lifting chain and the drill motor, this load cell will provide the necessary information to calculate hook load and WOB. Specifications are as follows: Linearity: ±0.03%, full scale Hysteresis: ±0.02%, full scale Repeatability: ±0.01%, full scale Creep (after 20 min): ±0.15%, Zero Balance: ±1%, full scale Operating Temp Range: -55 to 90°C (-65 to 200°F).

Accelerometer

Cost $ 1.59

Source: Digikey (http://www.digikey.com/product-search/en/sensors-transducers/accelerometers/1966355?k=accelerometer)

Placed on the drill motor to assess the vibrational signature during drilling to allow for the detection of different drilling conditions or unsafe vibrations in the motor assembly.

Wattmeter

Cost $17.57

Source: Amazon (http://www.amazon.com/P3-P4400-Electricity-Usage-Monitor/dp/B00009MDBU/ref=sr_1_1?ie=UTF8&qid=1448223635&sr=8-1&keywords=kill+a+watt)

While not part of the automation system, this will provide information regarding total power consumption at a given time. Accuracy for voltage, amperage and wattage are all within 0.2 percent

Proximity sensors

Cost $510.00

Source: omega.com (http://www.omega.com/pptst/LD701.html)

Two sensors used to measure the drill string's "orbit" in order to determine if the bit is traveling or if buckling is occurring. Sensor range is 2 to 5 mm, with an accuracy of +/- 10 µm.

Instrument Temp

Cost $ 1.59

Source: jameco.com (LM35DZ)

(http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_155740_-1)

This sensor will be used to monitor the temperature of the power and control hardware enclosure. This will be used to signal instrument cooling when needed to save energy and allow for safe operation. Operating range of 0 to 100°C with an accuracy of +/- 0.6°C.

Encoders

Used on separate parts of the drill string assembly to provide rpm data to the controller. These sensors can also be used together to help determine if twist off has occurred.

Stepper, drill, pump motor controllers

Cost: 42.99, 66.00, 134.00

Stepper: http://www.amazon.com/SainSmart-Micro-Stepping-Stepper-Driver-Bi-polar/dp/B00DFSF9GE/ref=sr_1_1?ie=UTF8&qid=1448224045&sr=8-1&keywords=stepper+drive

Drill: http://www.automationdirect.com/adc/Shopping/Catalog/Drives/DC_Drives/High_Voltage_(%3E_50V)_Open_Frame/GSD4-240-1C

Pump: http://www.automationdirect.com/adc/Shopping/Catalog/Drives/GS1_(120_-z-_230_VAC_V-z-Hz_Control)/GS1_Drive_Units_(120_-z-_230_VAC)/GS1-21P0

Signaled via the microcontroller to activate and precisely control the motors and pump. Built in controls allow for regulation of torque or flow rate with an accuracy dependent on the range used. Expected accuracy of +/- 1%.

Siren/Warning Lights

Activated to warn of imminent drilling, siren will sound once before drilling while warning lights will remain illuminated until drilling is completed.

Start Switch

Used to start or pause drilling, this switch only acts as a soft shut-off and will not completely isolate components from the power supply.

Emergency Shutoff

Disabling communication from the microcontroller and controllers, the emergency shutoff acts as a soft shutoff and also cuts the enable signal to stop future controls.

Communication

Thanks to the standardized protocols used for Wi-Fi transmissions, data can easily be sent from the Edison to the Pi while the Pi is also hosting data for other devices. This scheme allows the user to bear the processing cost of the graphics which in turn allows the Pi to store the data and transmit it to multiple devices without fear of diminished performance. A simplified communication scheme is shown below with the arrows indicating the transmission and receipt of data via a standard CAT5 cable.

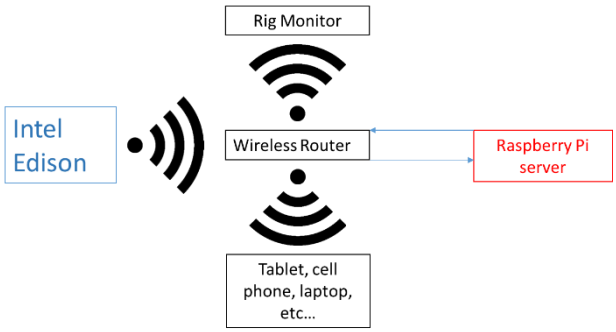

Figure 11 Simplified communication diagram

This will allow any and all data to be accessed by an authorized user on site. Further security measures can be added as necessary to secure the data. All other communications will be made using shielded wire from the sensors to the microcontroller in order to isolate the signals from as much noise as possible. To further safeguard electrical signals a Faraday cage will be installed around the power systems and controllers.

Budget

The proposed budget for this build is approximately $6,000 with ample room to cover additional expenses or alterations to the design. This is accomplished mainly by avoiding the cost of a full computer and data acquisition unit as well as using a programmable microcontroller in place of a typical PLC. This will require some extra work to use but the cost savings as well as the ability to use any sensor from any company was considered worth the effort. The preliminary itemized budget is shown below in Table 1 and totals $5,547.34 with $500.00 for shipping and machining respectively. The building materials are listed in both component cost as well as total cost due the number of each item being purchased, all other items are only listed as total cost. The main source of supplies is considered to be McMaster-Carr, although this may change if significant cost savings can be found.

Funding is being graciously provided by the department and university with commitments pending on the Phase I outcome.

Table 1 Itemized Budget

Description	Component Cost	Total Cost
Aluminum Extrusions (Single) 6 ft.	$ 19.79	$ 79.16
Aluminum Extrusions (Single) 2 ft.	$ 8.35	$ 100.20
Hardened Shaft	$ 7.19	$ 21.57
Shaft Holder	$ 34.10	$ 204.60
Linear Bearings	$ 69.33	$ 207.99
Mounted Ball Bearings	$ 11.78	$ 47.12
Drive Shaft	$ 11.13	$ 22.26
Position Control DC Motor	$ 143.33	$ 143.33
Motor Coupling	$ 20.11	$ 20.11
Three-Way External Connector	$ 9.86	$ 39.44
Right Angle Bracket	$ 5.60	$ 201.60
Drive Sprocket 11 Teeth	$ 13.83	$ 13.83
Lift Sprocket 72 Teeth	$ 59.57	$ 59.57
ANSI 35 Chain	$ 3.90	$ 23.40
Drill Motor	$ 434.44	$ 434.44
Coupling (motor to water swivel)	$ 20.11	$ 20.11
Water Swivel	$ 154.87	$ 154.87

Coupling (water swivel to drill pipe)	$	66.91	$	66.91
Drill Pipe	$	10.79	$	43.16
Pump	$	600.00	$	600.00
Intel Edison w/Arduino BoB			$	100.00
Raspberry Pi			$	38.76
Chain Cable Carrier			$	8.69
Screw terminal			$	6.24
Load Cell			$	100.00
Accelerometer			$	50.00
Temp/Pressure Sensor			$	20.00
Wire			$	50.00
Proximity Sensor			$	250.00
Solder			$	10.00
3-element strain rosette			$	22.00
Flow meter			$	100.00
Pressure Transducer			$	225.00
Temperature Sensor			$	1.59
Torque Cell			$	250.00
Control Switch			$	1.59
Laser Distance sensor			$	250.00
Gyroscope			$	1.65
Load Cell			$	175.00
Accelerometer			$	1.59
Wattmeter			$	17.57
Proximity Sensors			$	255.00
Stepper Motor Driver			$	42.99
DC Motor Driver			$	66.00
Shipping			$	500.00
Machining/Raw Materials			$	500.00

Total **$ 5,547.34**

Summary

In closing, the proposed design consists of an automated, AI controlled, data driven, optimization protocol to adapt to changing downhole conditions. The structure is to be constructed using t-slotted aluminum framing with an emphasis placed on mobility and modular construction. All motors and pumps have been selected to provide more than the calculated values while being well under the power limit for the competition. Design is centered on safety and efficiency with a slew of shutoffs and remote shutdown. The designed system is estimated to cost under $6,000 despite the cap of $10,000. This is all to be achieved without outside help, with the team providing all the labor and work for the entire project.

Upon acceptance into the next phase of the competition, an initial order will be sent to obtain the primary building materials and components for this project. While the rig structure is being completed, the control systems will be arranged and tested independently prior to being installed on the main structure. Lastly, all sensors will be tested and arranged on the structure to allow for the programming and testing to begin.

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