Optimal Control of Directional Drilling Process

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Petroleum Engineering Programme
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Approved by,

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May 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own expect as specified in the references and acknowledges, and that the original work contained herein have not been undertaken or done unspecified sources or persons.

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Name: Muhammad Syazwan bin Zainuddin

Date: 13 August 2014

ABSTRACT

As drilling environment is getting more challenging, with deeper, high pressure high temperature formation, and rough environment, ensuring that the bit direction following the planned and desired well path is very crucial in order to penetrate the reservoir targets. Current drilling operation employs the use of manual mode control of bit movement. Unfortunately, this manual mode of control may lead to some problem that arises from operational and human inaccuracies which make the actual path differ from the desired one.

This project will present a proposed algorithm and control strategy for automatic guidance of bit movement in directional drilling process where the knowledge of drilling operation and control system are being applied. In order to develop an optimal control strategy in guiding the bit movement, the kinematic and dynamic model of the drill string and bit movement has been derived at the first stage. Two dynamic system was analyzed in this study; the torsional behavior of the drill string and gyro model of the MWD system. In the second step, by using Matlab-Simulink Software, the system's kinematic and dynamic equations is model and simulate to predict the system's behavior. The result from the simulation is then analyzed and studied in order to determine the ability and limitation of the designed control system. It is shown that the proposed control system can generate an appropriate well path and hit the specified target. This automatic control system helps in reducing human and operational error which results in more accurate well path being generated while drilling.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

1.1 Background

The technique of directing a well along a predetermined course to hit the reservoir target is called the controlled directional drilling where the reservoir target or bottom hole target is located at certain distance and direction from a surface location. In directional drilling process, measuring while drilling (MWD) system is one of the most commonly used survey tools in the industry. There are two reasons which have led to the invention of MWD system; to navigate the drilling bit and tracking a desired path.

The MWD is a system that provides real-time information (hole inclination, azimuth etc) to assist in steering the drill. The data obtained from MWD is transmitted to surface through the mud pulse telemetry system. The mud pulse can be generated in three varieties:

i.	Positive pulse	: Restrictive valve inside the drillstring generate the pressure pulse.
ii.	Negative pulse	: Generated by a bypass valve from inside the drillstring and signal is send through the annulus.
iii.	Continuous wave	: Sinusoidal pressure fluctuations generated within the drilling fluid by gradually close and open the valve.

In directional drilling technology, the control of bit movement along the correct path is very important. MWD can survey bit movement and at have several abilities in leading bit movement along the correct path with the intervention of human operator. Figure 1 shows the human MWD system where the measuring signals from the MWD is analyzed and synthesized by human operator before any controlling command was delivered downhole.

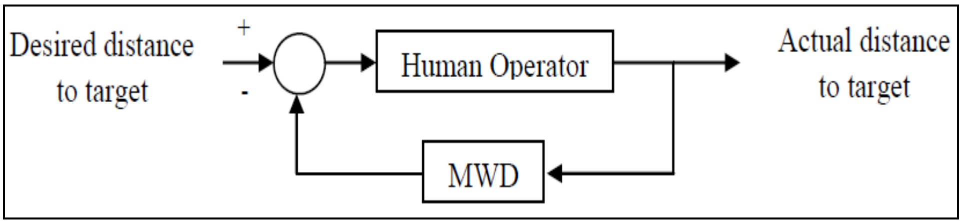


Figure 1: Manual feedback control system diagram

A lot of research and experiments have been conducted by a group of expert who compares the data location from MWD output with the drilling plan and tried to reduce the differences in bit movement.

1.2 Problem Statement

Prior to the advent of rotary steerable technology, directional driller controlled trajectories using non-intelligent drilling tools such as downhole motors. Drilling a directional wellpath using this technology was relatively inefficient and had adverse effects on wellbore placement and quality.

In the manual mode control of bit movement, some problem arises due to operational and human inaccuracies which make the actual well path differ from the desired one. This error may come from the limitation of the human operator to assimilate the MWD data, compare the actual well trajectory with the planned and take corrective actions to get back to the desired well plan.

Adjustment with correction run or command must be made when the borehole is deviated from the planned well path. With the current challenging drilling environment, this correction run must be applied quickly to avoid any drilling problem such as the risk of doglegs, which can later lead to some hole problems and failure of the drilling tools. If proper corrective action is not be taken, there is also a risk of not hitting the reservoir targets properly as per planned

In order to overcome this problem, a good control strategy of directional drilling process can be design in such a way that it helps in reducing the operational and human errors which in turn enable the well path to be drilled more precisely. Despite of reducing the well path distance error, this control system might also help in minimizing the drilling time and the drilling cost indirectly.

1.3 Objectives & Scope of Study

1.3.1 Objectives

In general, this project aimed to design an automatic guidance control system for bit movement in the directional drilling process. The objectives of this project are divided into two parts:

i. To study the kinematics and dynamics model of drill string and bit movement (to understand how the system behaves and works)
ii. To design a control strategy and proposed an algorithm for automatic guidance of bit movement in directional drilling process

The automatic control system is expected to be able to generate an appropriate wellpath and able to reach the specified target.

1.3.2 Scope of Study

Three scope of study have been identified in order to achieve project's objectives:

i. Directional drilling dynamics and kinematics system

   The knowledge and understanding on system's dynamic and kinematics is very important in order to determine and design the optimal control system for directional drilling process. The following topics will be cover in this project:

   - Direction and position synthesis
   - Tensional behavior of the drill string
   - Gyro system of MWD

ii. Control system

   The second scope of study for this project is to understand and implement the knowledge of control system in order to model an optimal control strategy for directional drilling process. A control system will be design in such a way that it will analyze and synthesize the position and direction data obtained from the MWD before a correcting command is delivered to correct the bit path. A feedback loop that describes the mechanism of the control system will also be developed.

iii. Optimization

Optimization means to produce the best possible result with the available resources. Optimization can be divided into three: time, cost, energy. For this project, a focus will be given on optimizing the energy. This can be achieved by minimizing the bit movement (distance error) between the actual wellpath with the desired one.

1.3.3 Relevancy and feasibility

Oil and gas exploration and production industry is the only industry that demands a more diverse set of human, mechanical and technological. Competition for natural resources has driven companies to explore and produce in harsh, remote and even hostile locations, where even the simplest of logistical tasks can be difficult and costly.

As the environment grows more diverse and unforgiving and the challenges more complex, skilled human resources are aging and growing scarce. Intelligent surveillance, utilizing downhole sensors to monitor wells, is key to moving the industry forward. The invention of this automatic control system might help in minimizing the drilling time, cost, energy and error that may be encountered while drilling in this harsh and challenging drilling environment.

CHAPTER 2

LITERATURE REVIEW

2.1 Directional Drilling

Vieira (2009) defines directional drilling as a unique drilling operation used when a well is intentionally curved to reach the bottom hole targets. The term ‘deviated well’ is commonly used to describe a well that follows an angular line from the surface to the target. The well must be drilled precisely by using planned directional parameters designed for the well. In case of the well steers off course, the trajectory must be redesigned and drilled to get the well back on track. According to Rabia (2003), there are several reasons of drilling a deviated well:

i. *Inaccessible location*: The target reservoir might be located under an obstruction which make the rigging up over the site is not possible. The obstruction can be either manmade or natural obstruction such as building, populated area or lake.

ii. *Drill multiple well from a single structure*: On offshore platform, drilling multiple well from a fixed location to reach several bottom locations are more economical viable.

iii. *Sidetrackin*g: Sidetrack from existing wellbore to avoid obstruction (such as stuck downhole tool that are left in the hole) or dry hole.

iv. *Horizontal we*ll: In some cases, the reservoir performance can be enhanced by drilling a well at angles or inclination of generally greater than 85 degrees.

The directional well can be drilled by using various technique, however the general concept remain the same: pointing the bit in the direction to be drilled (Asitier, 1990). Recently, controlled directional drilling has become a practice used to drill area once impossible to reach the target, and to do so economically and efficiently.

2.2 Measuring While Drilling

One of the biggest issue in directional drilling is to ensure that the actual well path follow the planned well path so that the target reservoir can be hit especially when drilling in harsh, high pressure high temperature drilling environment (Smith, 2012).

This can be done by controlling the bit position and movement. To ensure that the bit is pointing in the correct position, directional survey is very important. In directional drilling, both drift angle and direction must be determined at various depths to compare the actual course of the well with the planned course (Short, 2005). Measuring while drilling (MWD) is one of the most commonly survey tools being used in the oil and gas industry.

Lyons (1996) stated that there are two reasons which led to the invention of the MWD tools: tracking the desired path and navigating the drilling bit. The MWD tools are instruments that signal the surface with information about the wellbore and formation at the drill bit. It consists of accelerometer that measure earth's gravitational field and magnetometers that measure earth's magnetic field. This two element continuously measure the hole direction, inclination and tool face orientation. MWD tools typically consist of a power system, telemetry system, directional sensor and formation measurement tools (Vieira, 2009).

- Power system: Power is supplied to the tool by batteries or turbine. Turbine energy is abundant because it is supplied by fluid flow. On the other hand, the batteries can supply tool power without drilling fluid circulation.
- Telemetry system: The telemetry equipments are used to transmit data back to the surface in which the signals are sent via mud pulses, which are then interpreted by a pressure transducer in the stand pipe at the surface.
- Directional Sensor: Directional survey information will be detected by triaxial magnetometers and triaxial accelerometers
- Geophysical traces are transmitted for geosteering. These are the Gamma Ray detector and Resistivity.
- The pulses are converted into log data at the surface. Log plotting requires a depth tracking system and computer software.

Figure 2 shows the configuration of the measuring while drilling system at the rig site.

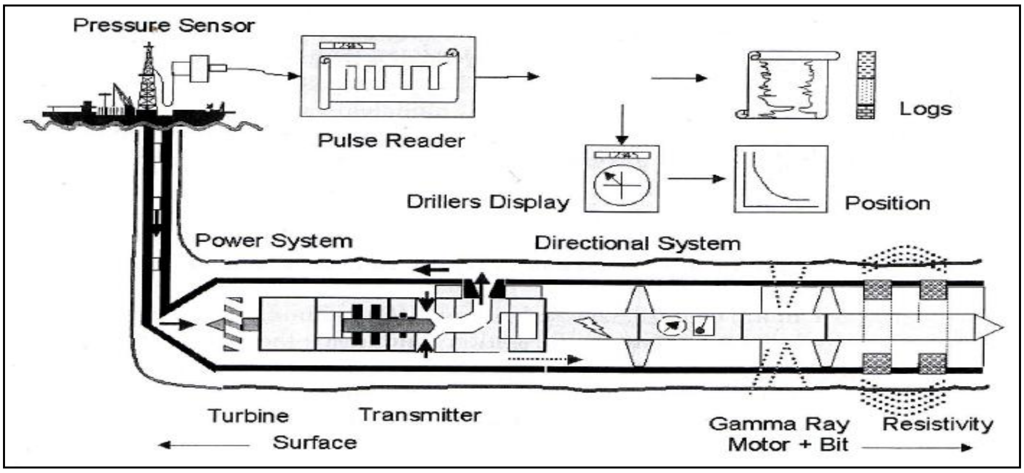


Figure 2: MWD at rig site

2.3 Human and Operational Error

The measuring signals from MWD system will be conducted by mud to the processing unit at the surface facilities. Once it reaches surface, the data will be analyzed and synthesized by human operator and the directional driller will make a decision whether the well has been drilled as per planned or not. If the actual path is deviated from the desired one, the toolface orientation of the deflection tool will be adjusted by sending controlling command through the mud pulse telemetry system. Asitier (1990) stated that there are two weaknesses in the human MWD system:

i. *Human error*: Such as human inaccuracies in interpreting the bit's position precisely. This may cause inaccurate correcting command to be transmitted to the system.
ii. *Operational error*: To decode electromagnetic signals or mud pulse, special algorithms and computers are used in all MWD systems. In some cases, poorly grounded generators and light plant have created sufficient disturbance or interference to prevent clear reception of the signals from MWD tools and this might as well affect the quality of the signals.

2.4 Rotary Steerable System

Before the introduction of the rotary steerable system (RSS), directional well was drilled by using non-intelligent tools such as downhole motor. Drilling the well with such a technology was relatively inefficient and had introduced a lot of error. The introduction of rotary steerable system (RSS) on the other hand had enabled fast, efficient and accurate wellbore placement and construction.

A rotary steerable system (RSS) is a form of drilling technology used in directional drilling. It employs the use of specialized downhole equipment to replace conventional directional tools such as mud motors. They are generally programmed by the measurement while drilling (MWD) engineer or directional driller who transmits commands using surface equipment (typically using either pressure fluctuations in the mud column or variations in the drill string rotation) which the tool responds to, and gradually steers into the desired direction. In other words, a tool designed to drill directionally with continuous rotation from the surface, eliminating the need to "slide" a mud motor.

These system do not use bent sub for affecting hole angles. Changes in hole angle are brought by the action of three pads contained within a non-rotating sleeves. The pads are kept in a constant contact with the formation by internal mud powered actuators. If no angle change is required, the system is put in neutral mode by pushing the pads in every direction thereby cancelling each other. If change in angle and direction is required, the electronics within the instruments cause each pad to extend against the side of the hole opposite the intended bias position. This is illustrated in Figure 3. The resultant action of these forces then cause the bit to build or drop angles required. This method is known as “push-the-bit” method.

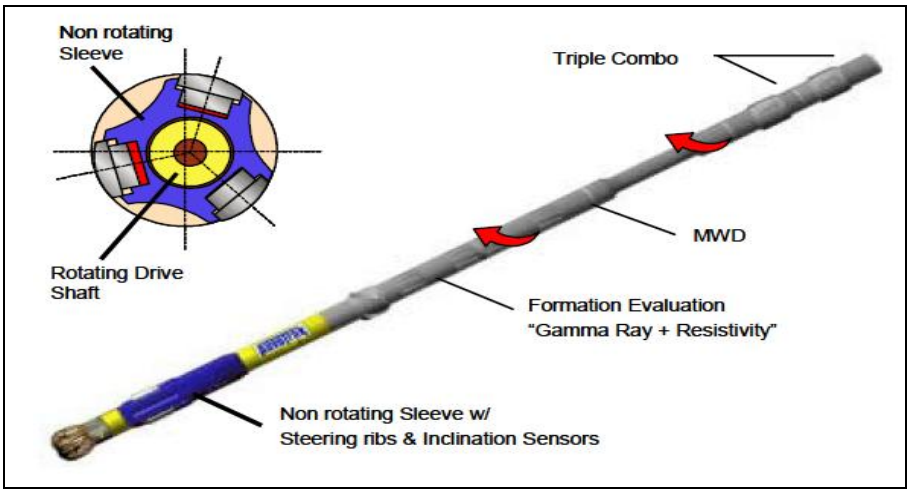


Figure 3: Autotrack, courtesy of Baker Hughes Inteq

The other method is known as “point-the-bit” method. Point-the-bit technologies cause the direction of the bit to change relative to the rest of the tool by bending the main shaft running through it. The latter require some kind of non-rotating housing or reference housing in order to create this deflection within the shaft.

2.5 Automatic Control System for Bit Movement.

The differences in bit movement between the actual wellpath with the desired one can be minimized by using automatic control system of bit movement. Automation is the introduction of control system and information technology to reduce the physical and/ or mental workload of human operators in charge of running a process. Automation is a step beyond mechanization, which assists operators by replacing human power by mechanical. In general, process automation is motivated by a desire to increase economic and/ or operational performances while making a process as safe as possible (Breyholts, 2012). Below are some researches which had been conducted in regards of the automatic control system.

C. Cockburn & J. Mathews (2011) in their research entitled “Automatic trajectory control in extended reach well” has proposed an automatic trajectory algorithm for RSS. The proposed control system is illustrated in Figure 4:

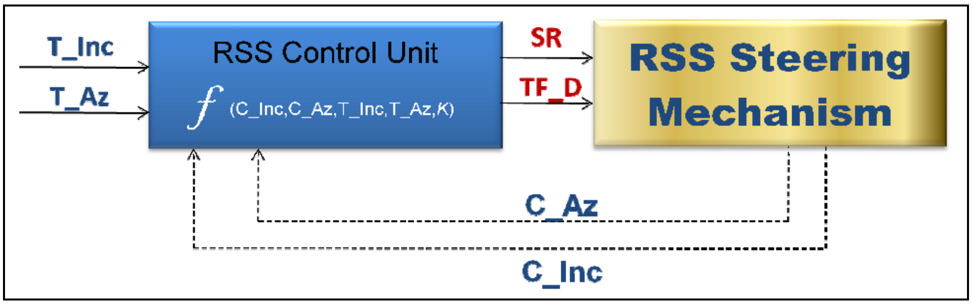


Fig. 4: RSS trajectory control diagram (C. Cockburn & J. Mathews, 2011)

The control system consists of two control loop; one that control the inclination and a second that controls the azimuth. The target inclination and azimuth are set by a downlink command, and then the control strategy will continuously sample the inclination (C-Inc) and azimuth (C-Az). These two variables will be compared with the target inclination and target azimuth. Then, the control strategy will produce the desired tool face (TF_D) and steering ratio (SR) to be performed by RSS steering mechanism to correct the bit path. The control strategy was tested on real field and the results shows that, by using the proposed control system, less BHA is run per section as the targeted reservoir layer are being tracked more successfully. And it is observed that the automatic control system also provide better inclination control and hence improve the well placement.

In different research, D. Pirovolou & D. Chapmen (2011) had proposed an automatic control system for rotary steerable system as shown in Figure 5.

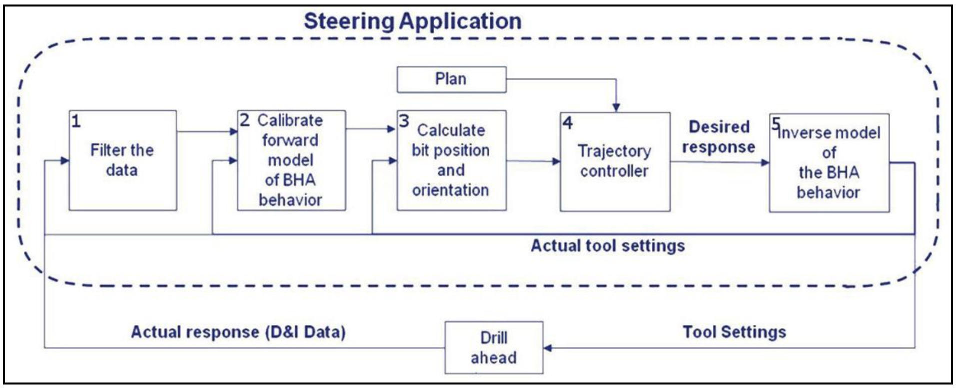


Fig. 5: Block diagram for trajectory control system (D. Pirovolou & D. Chapmen, 2011)

This is how the proposed control system works:

1) The raw inclination and azimuth data which can be noisy or corrupted is filtered and cleaned.
2) The second step is to calibrate forward model of BHA behavior and calculate the bit position and orientation.
3) Based on this calculated data, the trajectory controller will compare the actual position with the desired one.
4) Finally, the last step will produces the steering command to the RSS in order to correct the bit path

Figure 6 shows the wellpath generated using the suggested automatic control system in one of the well drilled in Venezuela. Blue line represents the planned well path and red line is the well path generated using the suggested control system. The result clearly shows that the proposed control system are able to produce an appropriate well path which is very close to the desired one and this in turn helps in minimizing the error which could be obtained from conventional manual drilling process.

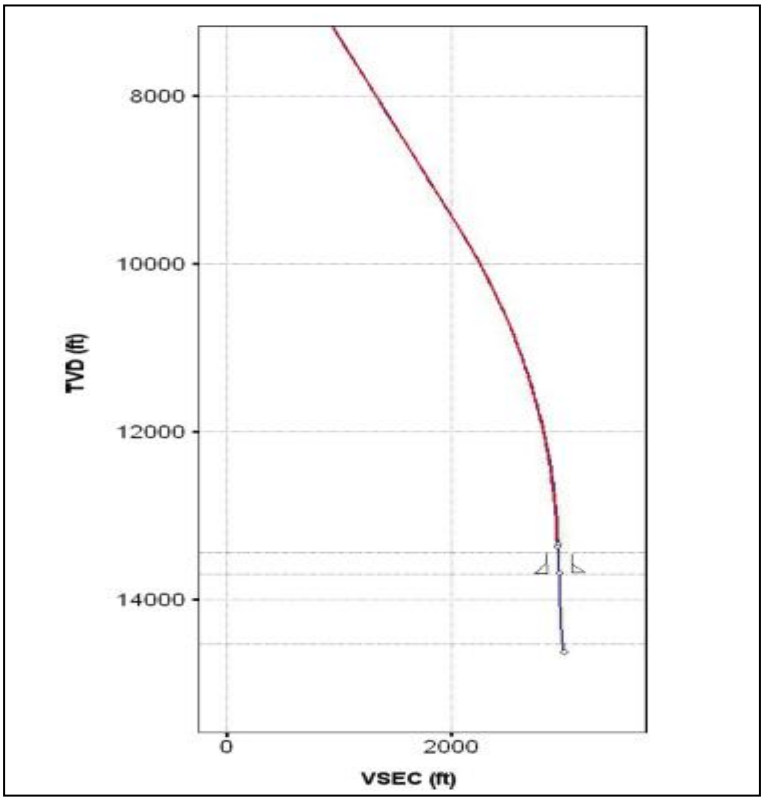


Fig. 6: Planned versus actual well path (a well in Venezuela)

The previous two researches are the automatic control system equipped in RSS system. A. Rouzgard & K. H. Shirazi (2011) on the other hand had designed an automatic control system based on bang-bang control strategy that is equipped with MWD system to lead the bit to the target.

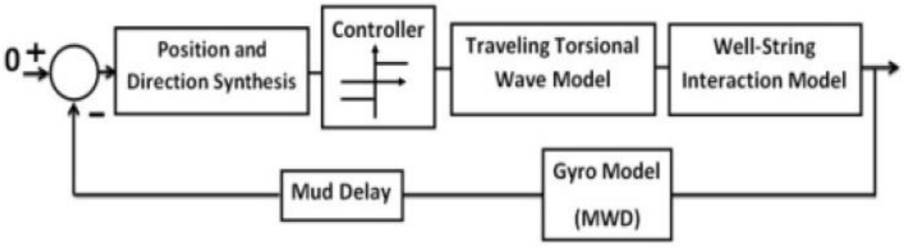


Figure 7: Feedback control system diagram (A. Rouzgard & K. H. Shirazi, 2011)

To evaluate the actual response of the control system, actual data from Nargesi field in south of Iran has been used. Figure 8 compare well no 1 path of Nargesi field which is generated by conventional manual drilling process(black line) and the simulated well path using the suggested automatic control system (blue line). It is seen that the simulated well can reach the target.

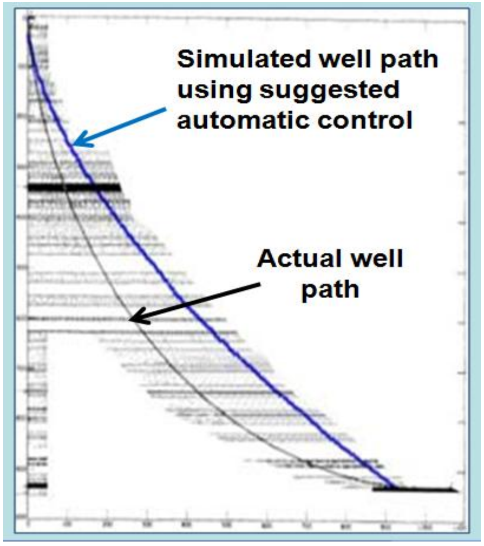


Fig. 8: Well path of No. 1 Nargesi field and the simulated path

CHAPTER 3

METHODOLOGY

3.1 Project Planning Flow

Basically, there are seven main stages of work that are involved in accomplishing this project, as shown in the Figure 9

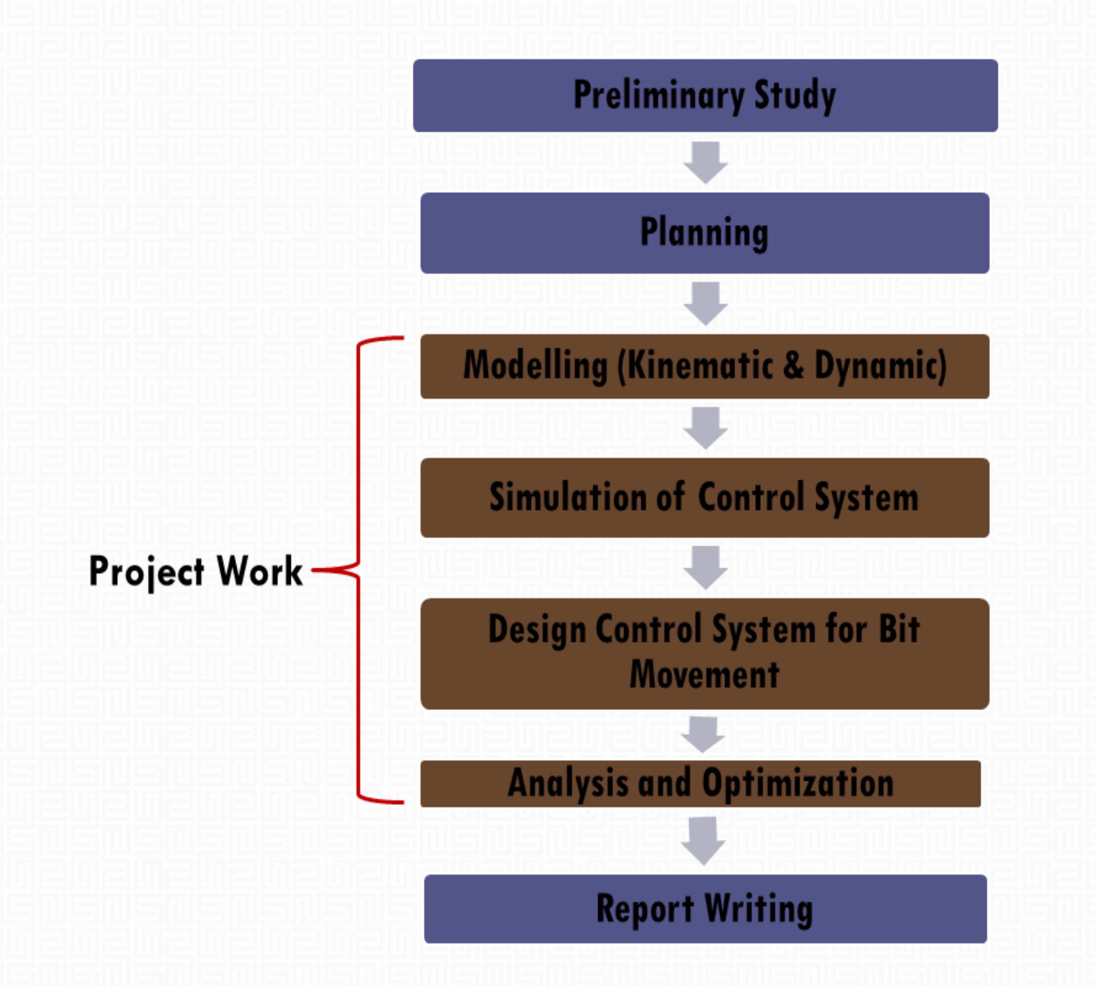


Figure 9: Project flow chart

The preliminary study includes identifying the problem faced by the industry, basic understanding on fundamental concept and theories and performing the literature review.

3.1.1 Modelling and Simulation of Kinematic System

The first step in the project work is the kinematic modeling and simulation by using Matlab software. Figure 10 shows the basic steps on how the model will be design in the Matlab programming.

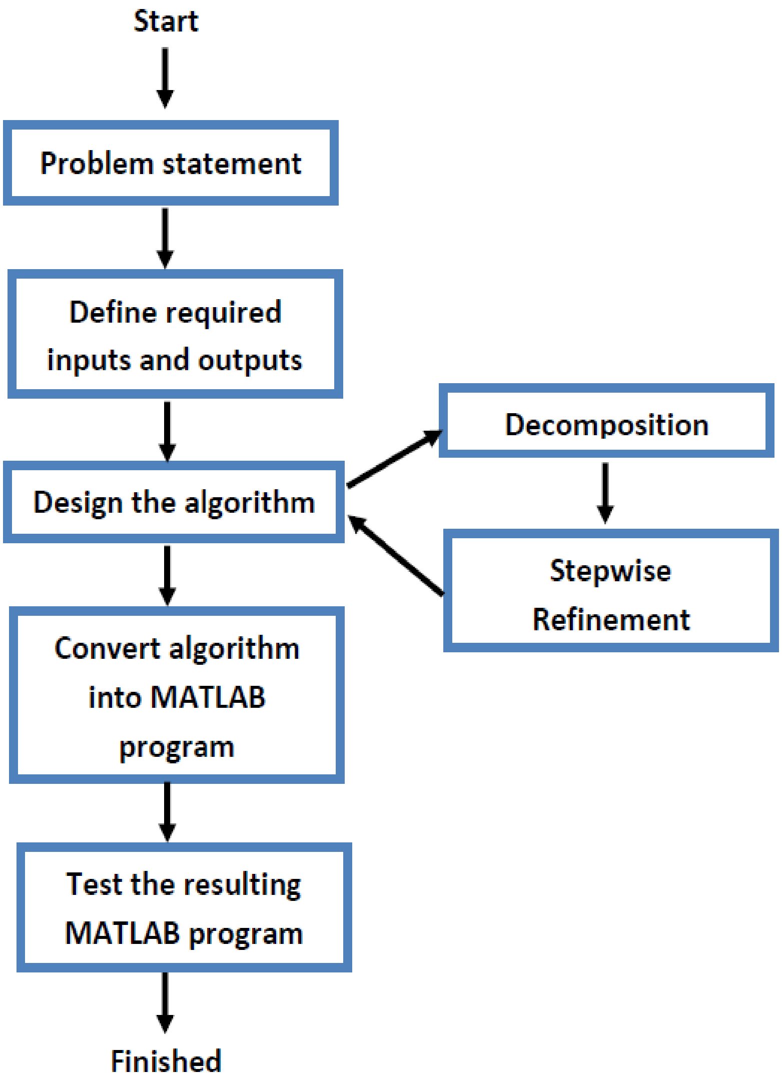


Figure 10: Basic steps in programming

3.1.2 Modeling and Simulation of Dynamic System

The steps of modeling and simulation of the dynamic system are as follows:

1. Derive the mathematical expressions that represent the dynamic system.
2. In modeling phase, models are built as block diagrams via a graphical user interface (GUI). A block diagram representing a dynamic system is

essentially an interconnection of blocks, each block corresponding to an operation carried out by a component, such that the blog diagram as a whole aggress with the system's mathematical model. Each block is identified with a transfer function G(s) = O(s) / I(s), also called the gain of the block, as shown in figure below:

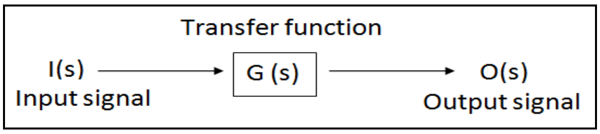


Figure 11: Schematic of a block

3. Build model (block diagram) in Mathlab Simulink software interface
4. Run simulation
5. Analyze result

3.1.2 Design a Control Strategy

Control is the process of manipulating, manually or automatically, the input of a dynamic system so that the system output will behave as desired. In this project, a feedback control system will be design. A feedback control system is a control system where the output signal is measured and fed back for use in computing the input signal. To analyze or design a feedback control system, a block diagram is usually drawn to show the major components and their interconnections in graphical form. Five essential components in feedback control system:

i. System we want to control
ii. A controller we need to design
iii. An actuator used to drive the control system
iv. A sensor used to measure the system output
v. The connecting lines in the block diagram carry signals

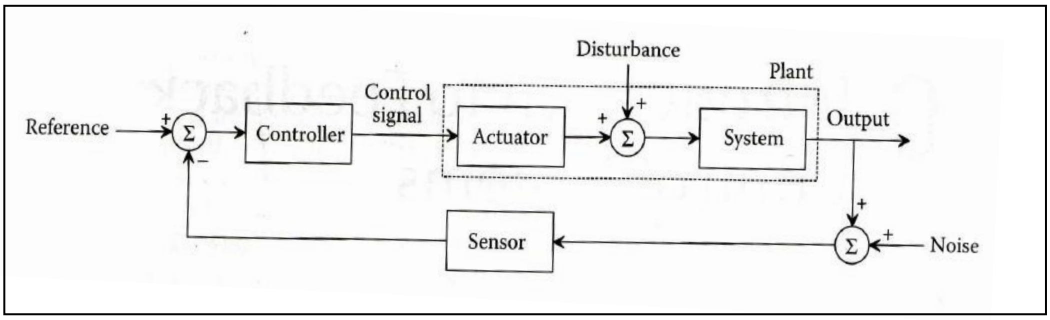


Figure 12: Block Diagram of an elementary feedback control

3.2 Project Activities and Key Project Milestone

The project timeline is divided into two parts to ensure that the project will be completed upon the end of FYP 2 period.

Figure 13: Project Activities and Key Project Milestone

3.3 Gantt Chart

Please refer **Appendix 1** for Gantt chart. The project milestone are indicated with red strip while process are indicated with blue strip

CHAPTER 4:
PROJECT WORK – MODELLING AND SIMULATION

4.1 Proposed Control System for Bit Movement

Figure 11 shows the proposed control system for automatic leading the drill string. The proposed control system works as follow:

1. The measuring signals from Measuring While Drilling (MWD) system are conducted by the mud through the mud pulse telemetry system to the processing unit.
2. In this processing unit, the position and orientation of the bit will be analyzed and synthesized. This is to determine if there is any different between the actual well paths with the desired one.
3. Based on the synthesized information, if the actual well path differs from the desired one, a controller will automatically send a controlling command to the system to change the bit position in order to correct the well path.
4. The controlling command is send to the actuator (used to drive the control system) to exert a +/- 180° rotation to the drill string for correcting the well path.

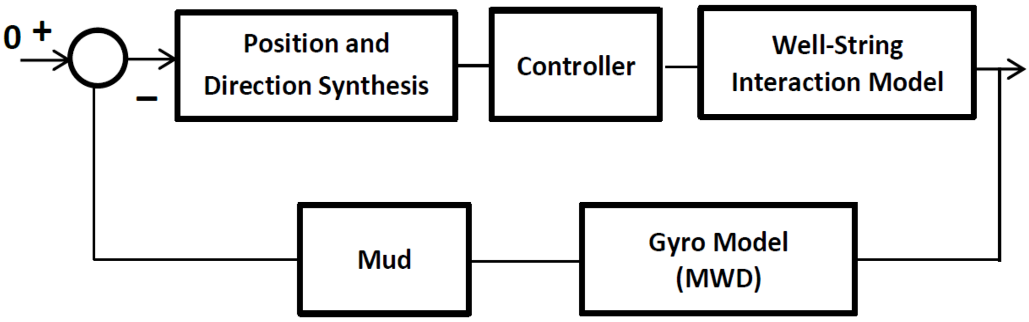


Figure 14: Proposed Feedback Control System Diagram

The suggested control system is based on the bang-bang control strategy. Bang-bang control strategy is a feedback controller that switches abruptly between two states. In this project, the control is restricted to be between a lower and an upper bound (3 degree to the left or 3 degree to the right) and the optimal control switches from one extreme to the other at certain times (i.e., is never strictly in between the bounds). The bang–bang controls frequently arise in minimum-time problems. This control strategy is implemented due to its simplicity.

4.2 Kinematics Prediction of Well Path

Kinematics modeling is conducted to study the motion of objects or systems by using equations, words, graphs and numerical numbers. Kinematics study aimed at explaining the motion of the objects or systems without considering what causes the motion and gives a better understanding on how the system works. In this section, kinematic prediction will be used to decide the well path. It is assumed that the drilling direction is decided first through the kinematic prediction regardless of any dynamic effects.

4.2.1 Position and Direction Synthesis

In this project, the tangential method of surveying bit position will be used where the wellbore is assumed to be a straight line throughout the course length. According to this method, the system will try to keep the slope of the actual path near to the correct slope. Downhole motor with bent sub is one of the most commonly used methods for deflecting wells. The bent sub is located directly above the motor and its pin is offset at an angle of 1-3 degrees. Figure 9 shoes the schematic of downhole motor with bent sub.

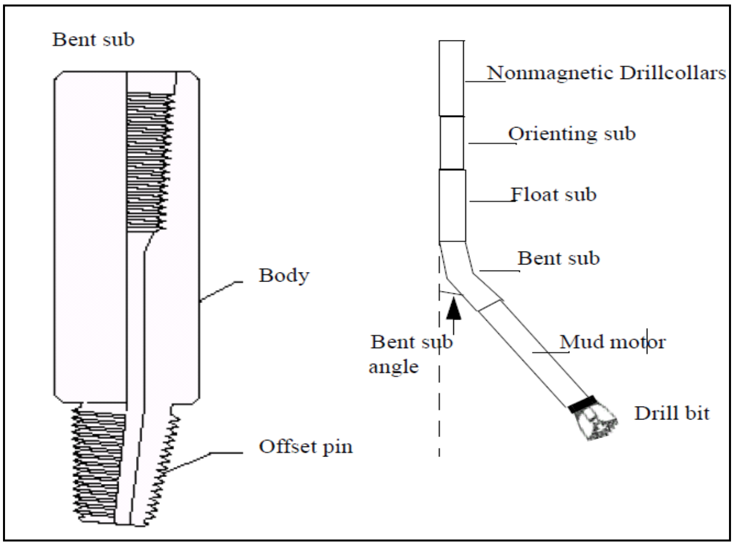


Figure 15: PDM BHA with bent sub

Depending on the path designer's decision, the angle of the bent sub can be adjusted between 0 – 3 degrees but in this project, the angle is fixed at 3 degree. It is assumed that the bent angle can only be change before the commencement of the drilling operation. The algorithm for bit position and direction synthesis can be explained as below:

i. The coordinates of kick off point (KOP) and drilling target are defined.

ii. A line is constructed to connect the KOP to the targets. The slope of this line is denoted by ***So***.

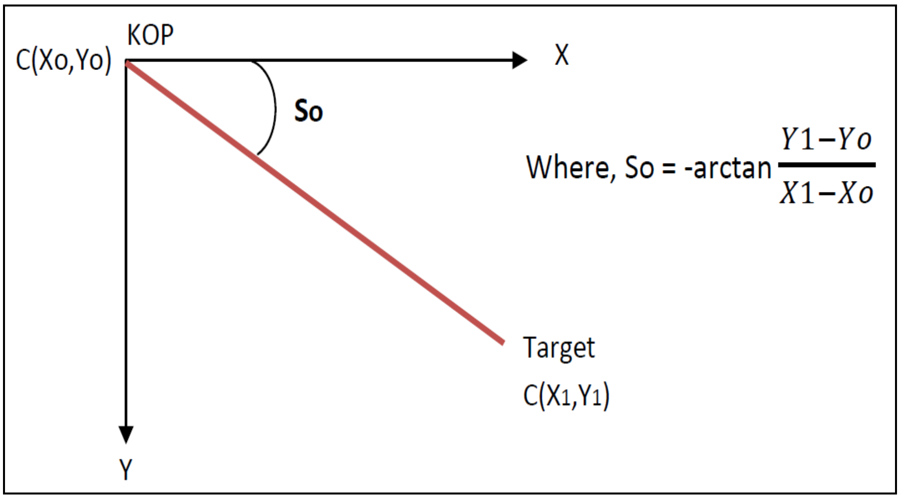


Figure 16: Target Line of Sight

iii. On the other hand, the drilling direction is represented by the blue line where the angle between drilling direction and x-axis is denoted by ***f***.

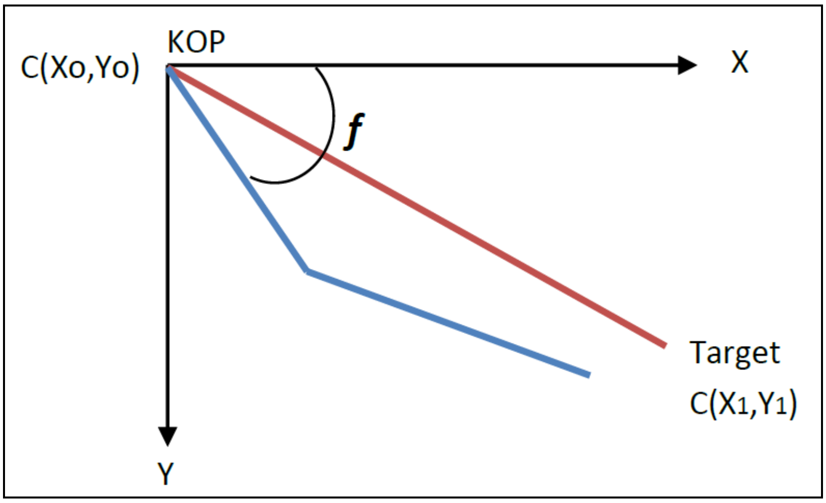


Figure 17: Two Successive Steps of Bit Movement

iv. The value of ***So*** and ***f*** will be compared in each time. When the slope of the bit's path ***f*** is more or less than ***So***, the controller rotates the drill string 180 degree to correct the bit position in order the hit the targets. Therefore in the next step, the well path deviation from target line of sight becomes smaller. The smaller the deviation of the drilling direction from the target line of sight, the more accurate path generated. The flowchart of guidance procedure for bit movement is shown on the next figure. **(This flowchart procedure is run into Matlab software for simulation. The Matlab coding for this simulation can be obtained from Appendix 2)**

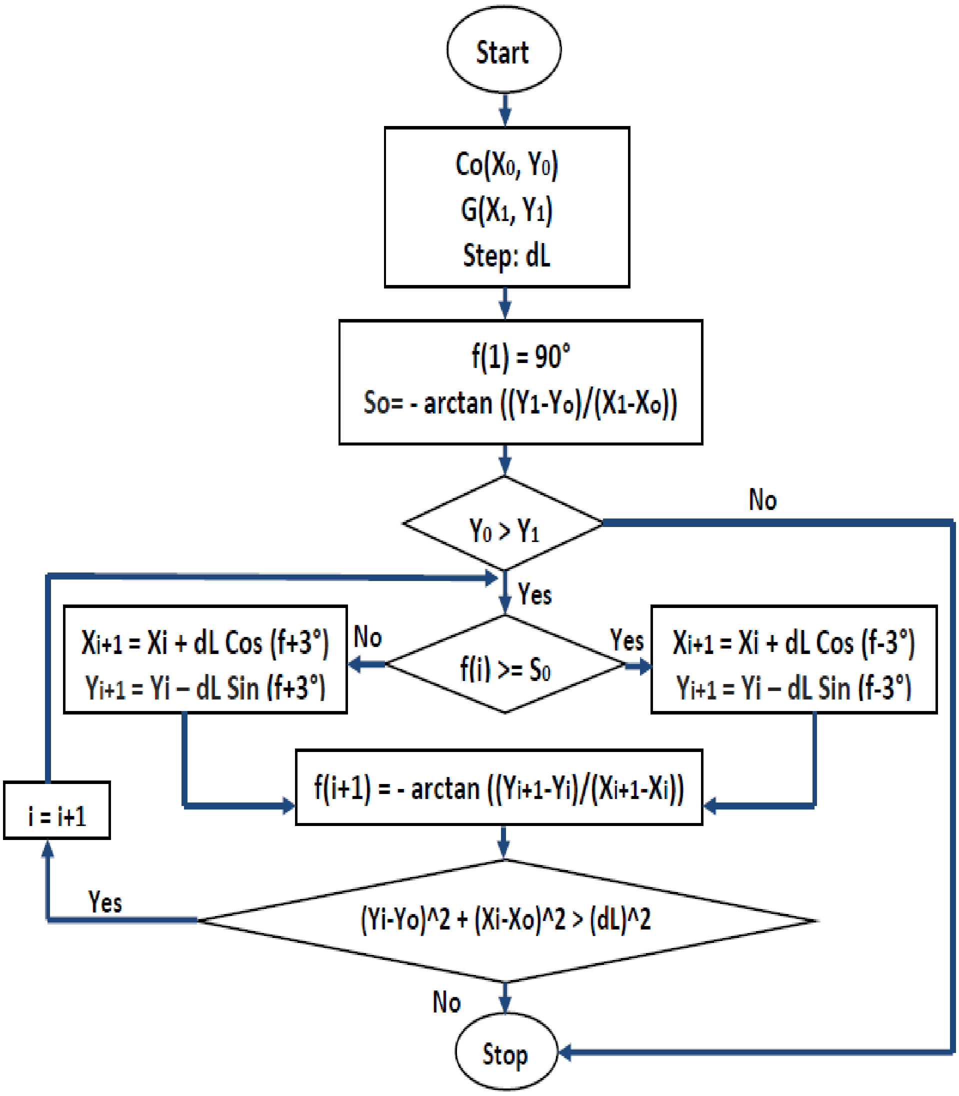


Figure 18: Flowchart for Position and Direction Synthesis

The detail descriptions of this flowchart are as follow:

i. Key in the input: initial coordinates (Xo,Yo), target coordinates (X_1,Y_1) and step size. In this project, the step size will be the length of the drill pipe. Three sizes will be used: 7.01 m, 9.75 m, and 13.72 m.

ii. Initialize the angle between the drilling directions to the x-axis at 90 degree (angle at kick off point, before deflection). ***f*** = 90 degree.

iii. Calculate the slope of the line that connects KOP to the target, ***So***.

$$\mathrm{So} = \text{-artan}\,\frac{Y1-Yo}{X1-Xo}$$

iv. Check if Yo > Y_1 to ensure that drilling progress downwards

v. Compare ***f*** angle with ***So*** angle. If (f >= So), move 3 degree to the right.

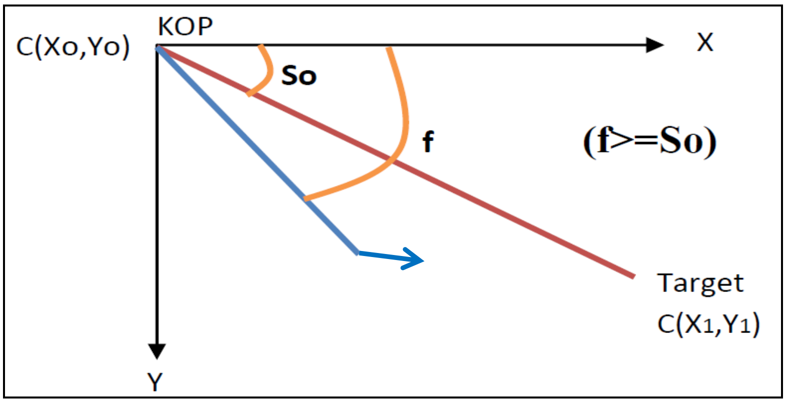


Figure 19: f greater than So

If If (f < So), move 3 degree to the left.

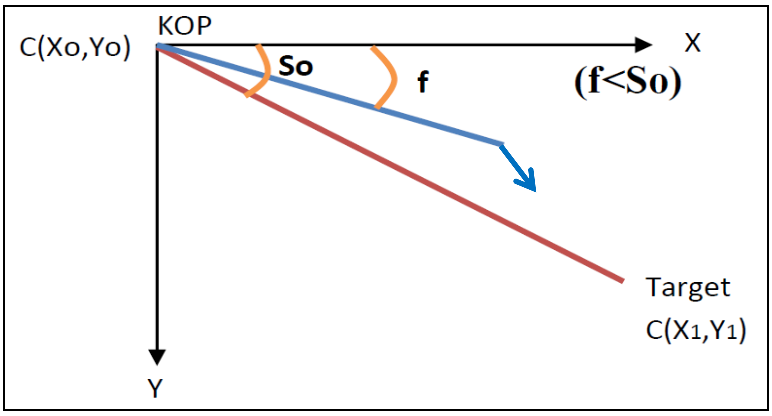


Figure 20: f less than So

vi. The above step will give us a new drilling direction. The angle between the new drilling direction and the x-axis is recalculated and the process is repeated until the specified target is reached.

4.3 Modelling of the Dynamic System

In this project, a second order system will be used to model the dynamic behavior of a system. The second order system is selected for analysis because they are the simplest system that exhibit oscillation and overshoot. Besides, many important systems exhibit a second order behavior. Second order behavior is part of the behavior of higher order system and understanding the second order system helps to understand the higher order system.

A second-order system exhibits a wide range of responses that must be analyzed and described. This system can be described by the transfer function shown below:

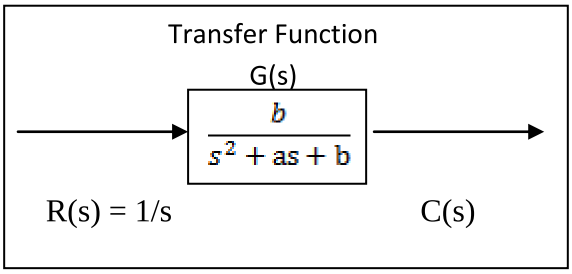


Figure 21: Second-Order System

Where a and b is the parameter needed to show all possible second-order transient responses. There are two physically meaningful specifications for second-order systems. The two quantities are called *natural frequency* and *damping ratio.*

i. Natural Frequency, ω_n

Natural frequency is the frequency at which a system tends to oscillate in the absence of any driving or damping force. (Example, the frequency of oscillation of drillstring)

ii. Damping Ratio, ζ

The damping ratio is a dimensionless measure describing how oscillations in a system decay after a disturbance.

$$\zeta = \frac{\text{Exponential decay frequency}}{\text{Natural frequency } (\frac{\text{rad}}{\text{second}})} = \frac{\text{Natural Period (seconds)}}{2\pi\ \text{(Exponential time constant)}}$$

Equation 1: Damping Ratio

Based on the understanding of the principle of the pole system, it can be summarized that **$b = \omega_n^2$** and **$a = 2\ \zeta\ \omega_n$**, so a second order system can be represented by the following formula:

$$\boxed{G(s) = \frac{\omega_n^2}{s^2 + 2\,\zeta\,\omega_n\, s + \omega_n^2}}$$

Equation 2: General Second Order Equation

4.3.1 Modelling of Torsional Behavior of the Drill String

In general, the total length of the drill string consist of 90% of drill pipe sections, 80% of its mass, with drill-pipe to borehole ratio of around 3 has larger clearance than the BHA. The drill string in overall is a long and slender structure. The dynamics and geometrical behavior of the drill string must be properly analyzed to better understand the underlying phenomena. Specifically, it is important to study the behavior of the drill pipes while operating under torsional vibrations. Under stick-slip oscillations, the torque on the drill string will be increases. This increase of torque in turn may result in torsional buckling of drill pipes and hence incurring in a helical configuration. In the process of changing from straight to helical shape, the apparent length of the drill string will reduce and hence will affect the contact forces at the bit-rock interface.

Richard (1991) shows that a second order linear transfer function can be employed to model the torsional compliance of the drill string.

$$\boxed{C_t(s) = \omega_{nt}^2 / [S^{2\,+}\, 2\,\zeta_t\, \omega_{nt}\, S + \omega_{nt}^2]}$$

Equation 3: Torsional Compliance of the Drill String

Where:

C_t = Torsional compliances of drill string

ω_{nt} = Torsional natural frequency of the string

ζ_t = Damping ratio

The natural frequency of the drill string depends on several factors:

i. Angle of the well

ii. Weight on bit

iii. Viscosity of drilling mud

The values of parameters are listed in Table 1. This value is obtained from Well Number One in Nargessi field, Iran [9].

4.3.2 Modelling of the Gyro of MWD System

Richard (1991) and Wiki (2010) shows that the dynamic model of the gyros of the MWD system can be estimated by a second order transfer function in S-domain as follow:

$$\boxed{C_g(s) = \omega_{ng}^2 / [S^{2\,+}\, 2\,\zeta_g\, \omega_{ng} S + \omega_{ng}^2]}$$

Equation 4: Dynamic of Gyro of MWD System

Where:

ω_{ng} = Gyro natural frequency

ζ_g = Gyro damping ratio

The values of parameters are tabulated in the following table:

Parameter	Value	Unit
ξ_g	$1/\sqrt{2}$	---
ξ_t	0.95	---
ω_{n_g}	100	HZ
ω_{n_t}	6	HZ
c_L	6	m/s
c_s	1992.88	m/s

Table 1: Quantity of Parameters

4.3.3 Simulation of Dynamic System

In order to evaluate the effects of dynamics on wellpath generated, all the dynamic system (torsional behavior of drill string and gyro model of MWD) are integrated into one block diagram, each block corresponding to an operation carried out by a component. Each block is identified with a transfer function as stated earlier in section 4.31 and 4.3.2 for well string and gyro model of the MWD respectively. The integrated blog diagram is shown in Figure 22.

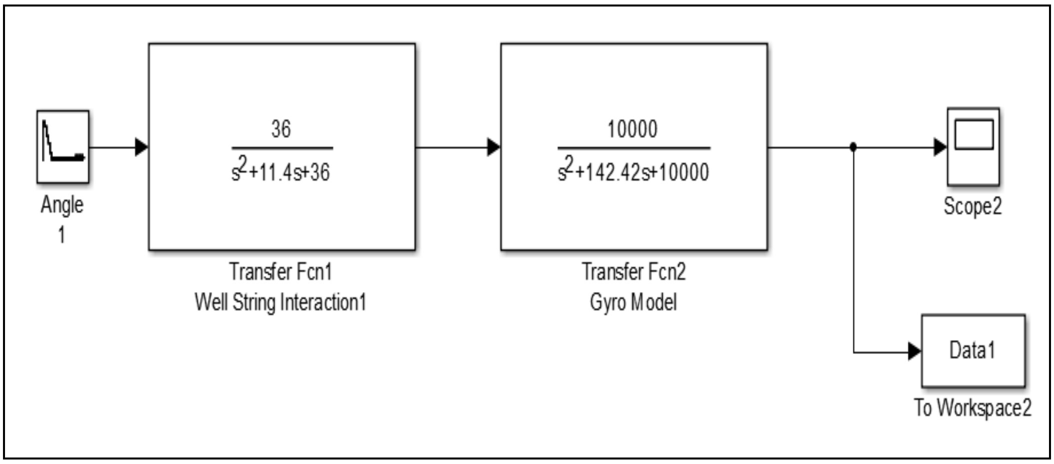
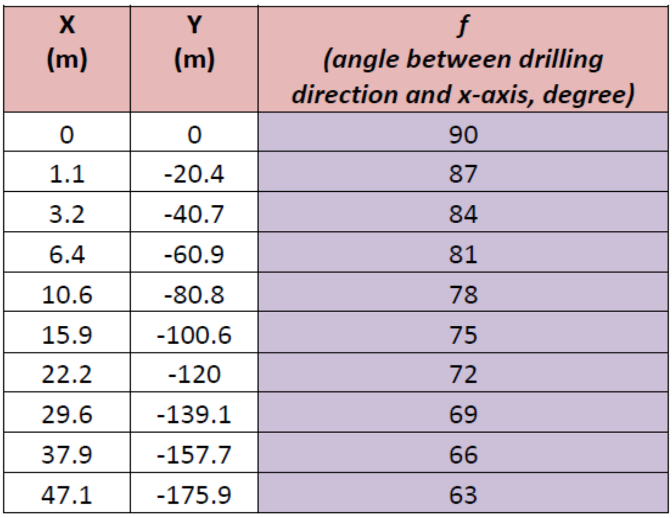


Figure 22: Block Diagram for Dynamic Analysis of Automatic Path Tracking Control in Matlab-Simulink

The input to this block diagram will be a series of angle generated from the kinematics prediction (angle between drilling direction and x-axis). These are the angle starting from the kick off point (90 degree) until the angle obtained at the target. Table 2 shows example of a series of angle generated from kinematics prediction for 10 successive steps of bit movement.



X (m)	Y (m)	*f* *(angle between drilling direction and x-axis, degree)*
0	0	90
1.1	-20.4	87
3.2	-40.7	84
6.4	-60.9	81
10.6	-80.8	78
15.9	-100.6	75
22.2	-120	72
29.6	-139.1	69
37.9	-157.7	66
47.1	-175.9	63

Table 2: Series of Angle Generated from Kinematics Prediction

4.4 Simulation

The simulation of the kinematic and dynamic model of the system was conducted to evaluate the actual response of the control system. The simulation is run to evaluate whether or not the proposed control systems are able to generate an appropriate well path and hitting the specified target. In this project, only 2-Dimensional (2D, zero azimuth) well will be considered. The targeting point is located at a depth and distance as stated below:

X : 1250 m
Y : -1150 m

The length of the drill pipe is considered as step size as the drilling progress forward. Three standard length of drill pipe as stated in the 'API Specification of Drill Pipe' **(Appendix III)** are used in this simulation:

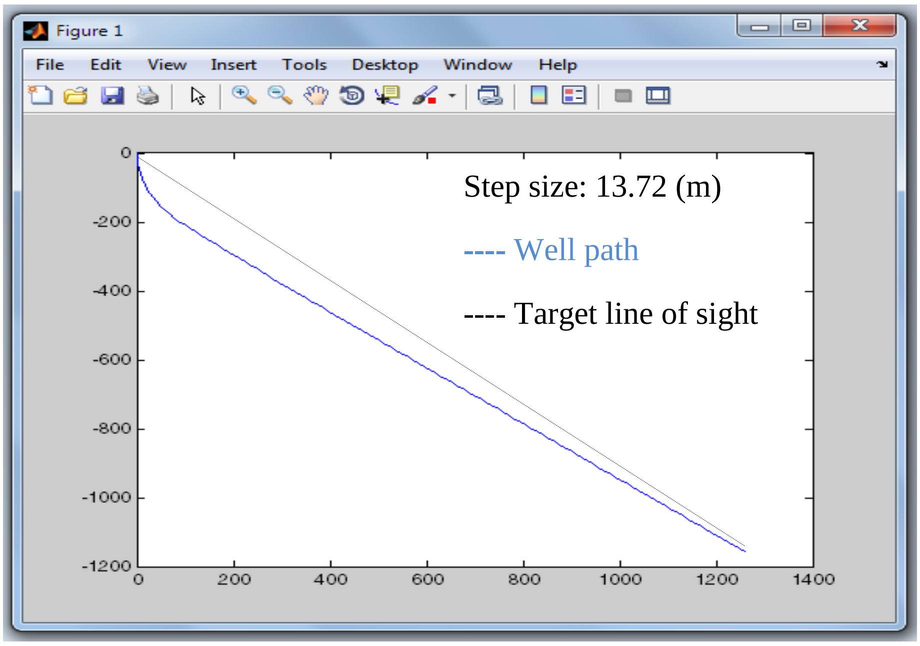
- 7.01 meter
- 9.75 meter
- 13.72 meter

CHAPTER 5

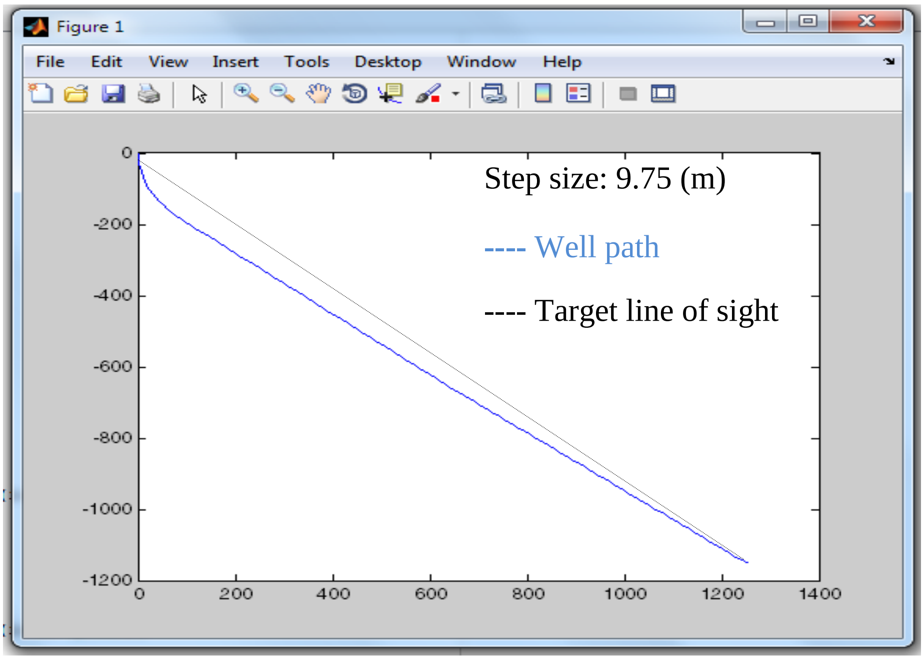
RESULTS AND DISCUSSION

5.1 Wellpath Generated from Kinematic Prediction (Position and Direction Synthesis)

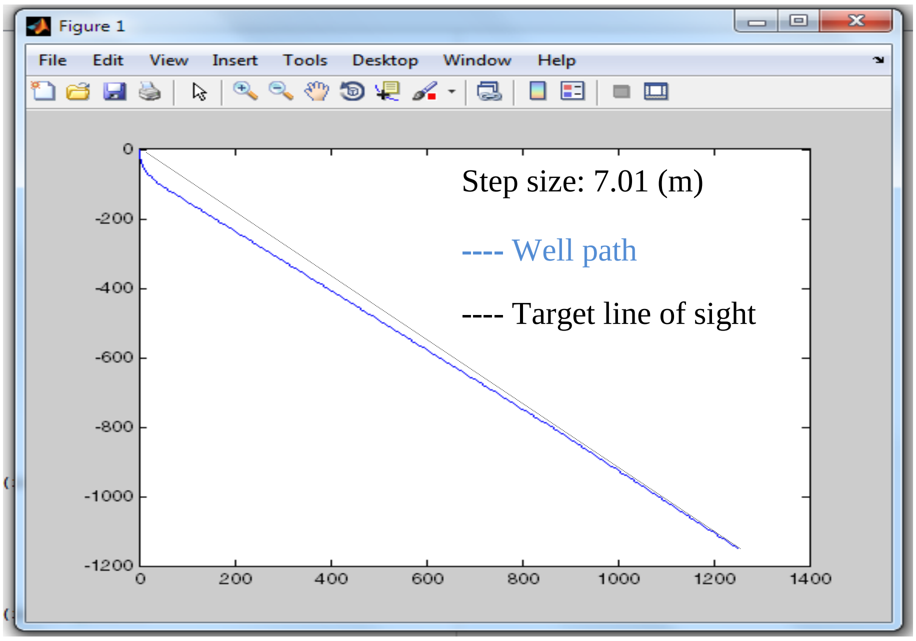
Based on the kinematic model developed in section 4.2.1 for position and direction synthesis, a simulation is run to evaluate the response of the proposed control system. Figure 23(a) to (c) shows the simulated wellpath using the suggested automatic control for three different step sizes. For each graph, the x-axis represents the displacement in the horizontal direction while the y-axis represents the displacement in the vertical direction. This wellpath is generated from kinematic prediction where it is assumed that the drilling direction is decided first through the kinematic prediction regardless of any dynamic effects.



(a)



(b)



(c)

Figure 23: Generated path (blue line) for three different step sizes

The dotted black line represented the target line of sight. As mentioned earlier, the smaller the deviation from target line of sight, the more accurate well path generated. A comparison between Figure 23 (a) to (c) reveals that:

1) The larger the step size, the more the curvature of the path and more deviation from target line of sight

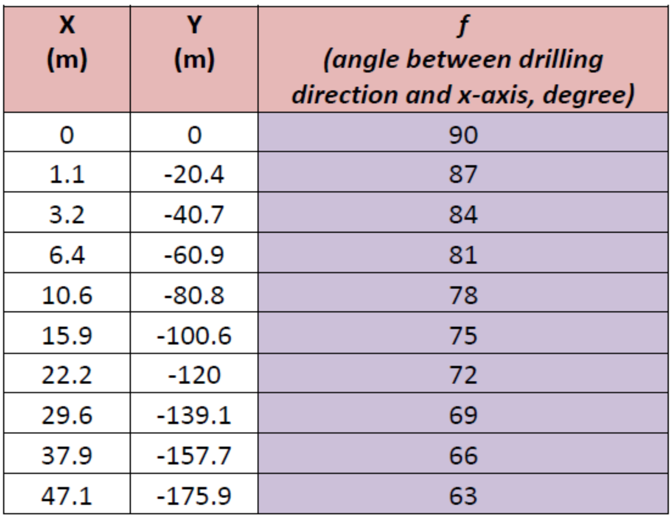
2) Regardless of the step size, the bit reaches to the specified target of (X: 1250 m; Y: -1150 m)

The results shows that the proposed control system has the ability in controlling the bit movement by changing the next point position until it reach the target.

5.2 Effects of Dynamics on Generated Angels from Kinematic Prediction

The analysis presented previously in section 5.1 is purely kinematic. In real application, the dynamics of a system must be taken into account as this might change the output value. For example, in directional drilling, to change the angle from 90 degree to 87 degree, we might get 87 degree as the output if only kinematics is considered. However, when dynamics is introduced into the system (formation, drill cuttings, mud, drill string etc), the output might not be exactly the same as what we expected.

Hence, to evaluate the real ability of the proposed control system to generate appropriate well path and penetrating the target, the dynamic system must also be evaluated. Table 2 shows example of a series of angle generated from kinematic prediction (section 5.1) for 10 successive steps. These values are input into the block diagram of dynamic system (section 4.3.3) to predict the next angle position after dynamic has been introduced into the control system.



X (m)	**Y (m)**	***f* *(angle between drilling direction and x-axis, degree)***
0	0	90
1.1	-20.4	87
3.2	-40.7	84
6.4	-60.9	81
10.6	-80.8	78
15.9	-100.6	75
22.2	-120	72
29.6	-139.1	69
37.9	-157.7	66
47.1	-175.9	63

Table 2: Series of Angle Generated from Kinematics Prediction

The simulation was run and Figure 24 shows the step response of this dynamic behavior. The step response of the dynamics shows that the system will settle at a sample time of 2 seconds. That’s mean, at a sample time of 2 seconds; we will obtain the angle almost the same as what we obtained from kinematic prediction. It is important to know at what time the system will settle because in normal operation, we usually want to change the direction after the system has stabilized and reach the desired value so that an appropriate well path will be generated.

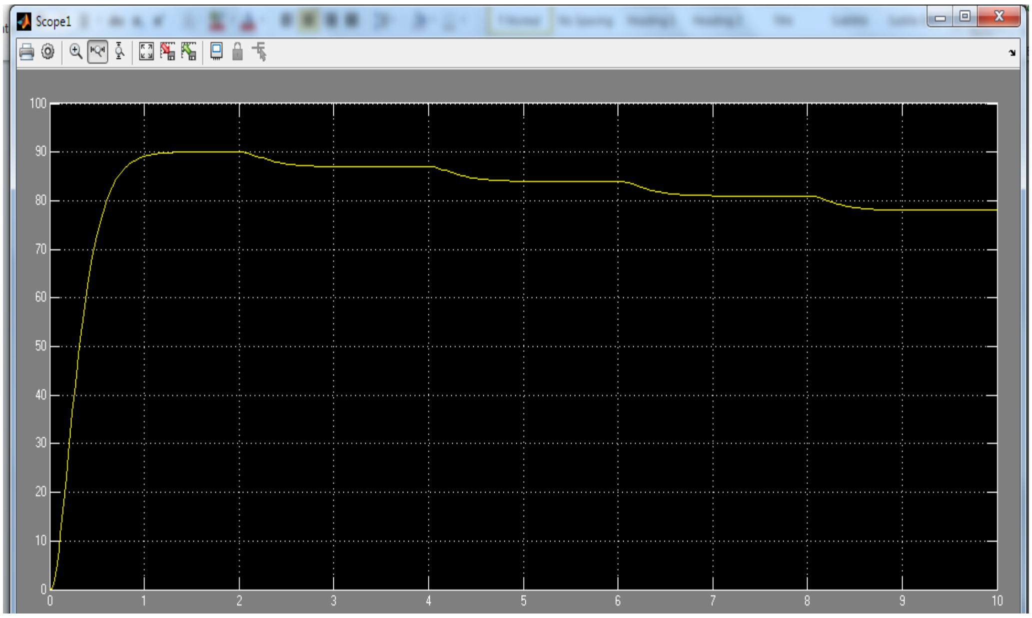
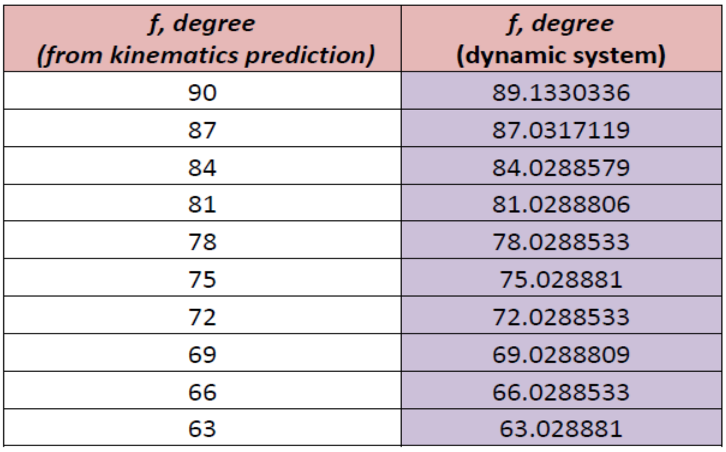


Figure 24: Step Response at Sample Time of 2 seconds

At sample time of 2 seconds where the system settles, the following angles are obtained for 10 successive steps of bit movement:



f*, degree** ***(from kinematics prediction)	***f*, degree** **(dynamic system)**
90	89.1330336
87	87.0317119
84	84.0288579
81	81.0288806
78	78.0288533
75	75.028881
72	72.0288533
69	69.0288809
66	66.0288533
63	63.028881

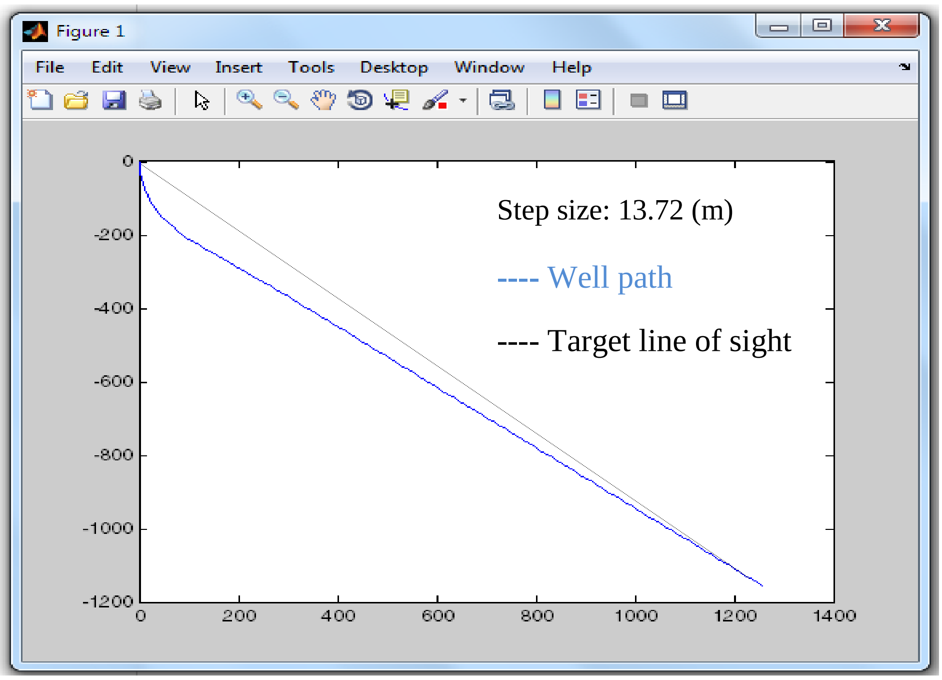
Table 3: Series of Angle Generated from Dynamic System Analysis

It is observed that the angle generated is almost the same as those obtained from kinematic prediction. Based on this actual angle position, the well path generated from the kinematic prediction previously will be adjusted to determine the actual well path. The actual angle position is used to calculate the new X and Y position for each successive step of bit movement and the well path is regenerated.

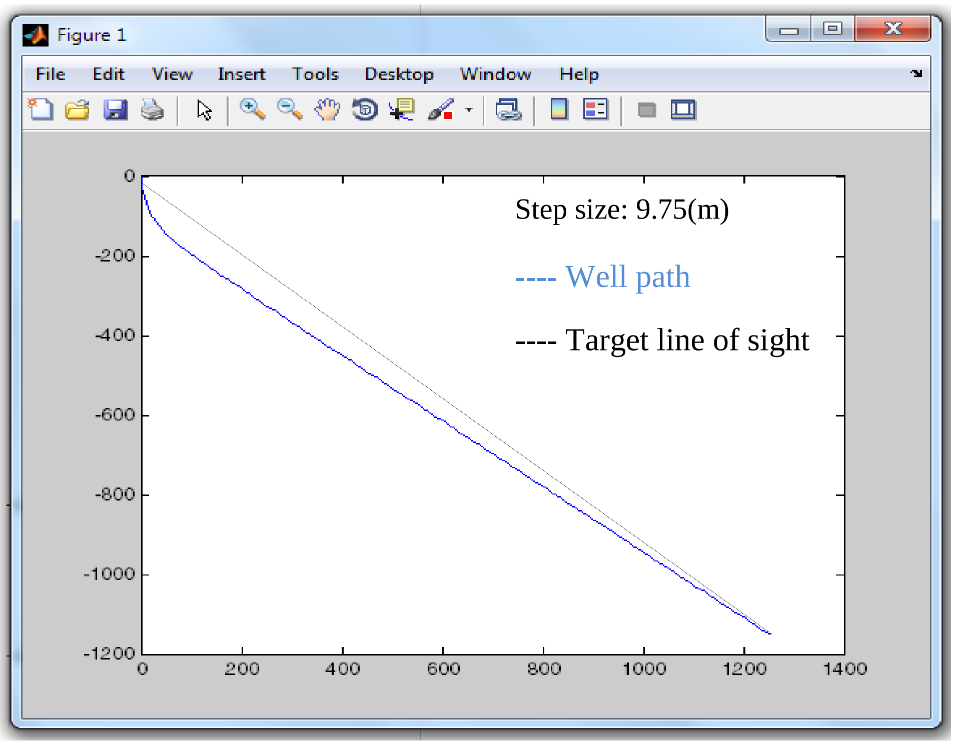
5.3 Effects of Dynamics on Generated Wellpath

Figure 25 (a) to (c) shows the simulated wellpath using the suggested automatic control system for three different step sizes with the inclusion of dynamic effect. As the dynamic settle down very fast, the result shows that the dynamic does not make much impact on the well path curvature and deviation from the target. A comparison between Figure 25 (a) to (c) shows the same observation as in kinematic prediction where:

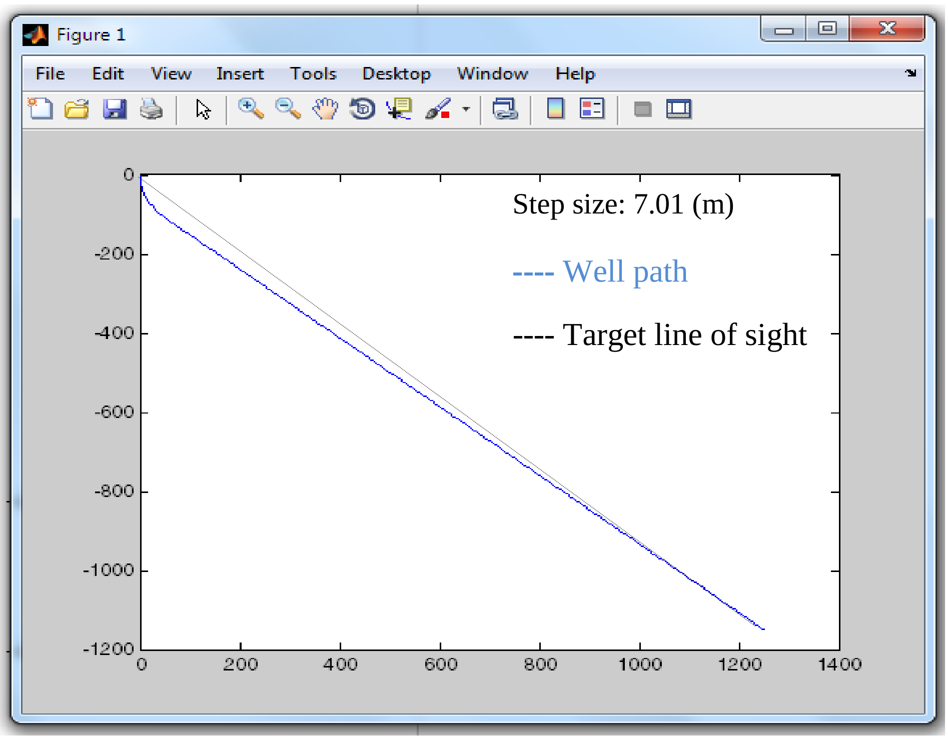
1) Regardless of the step size, the bit reaches to the specified target of (X: 1250 m; Y: -1150 m). This illustrates the ability of the control system in guiding the bit movement along the correct path to hit the target.
2) The larger the step size, the more the curvature of the path and more deviation from target line of sight. So the use of shorter length of drill pipes helps in generating a more accurate well path.



(a)



(b)



(c)

Figure 25: Generated path (blue line) for three different step sizes (dynamic)

5.4 Effects of Sample Time on Generated Angles

If a shorter sample time is taken (let say, sample time = 1 second), the system do not have much time to settle at the desired angle. As a result, the angles generated will be far different from the expected value and this will cause more deviation and curvature of the well path. The step response at sample time of 1 second is shown in figure 26 and the angle generated at this time sample is shown in Table 4:

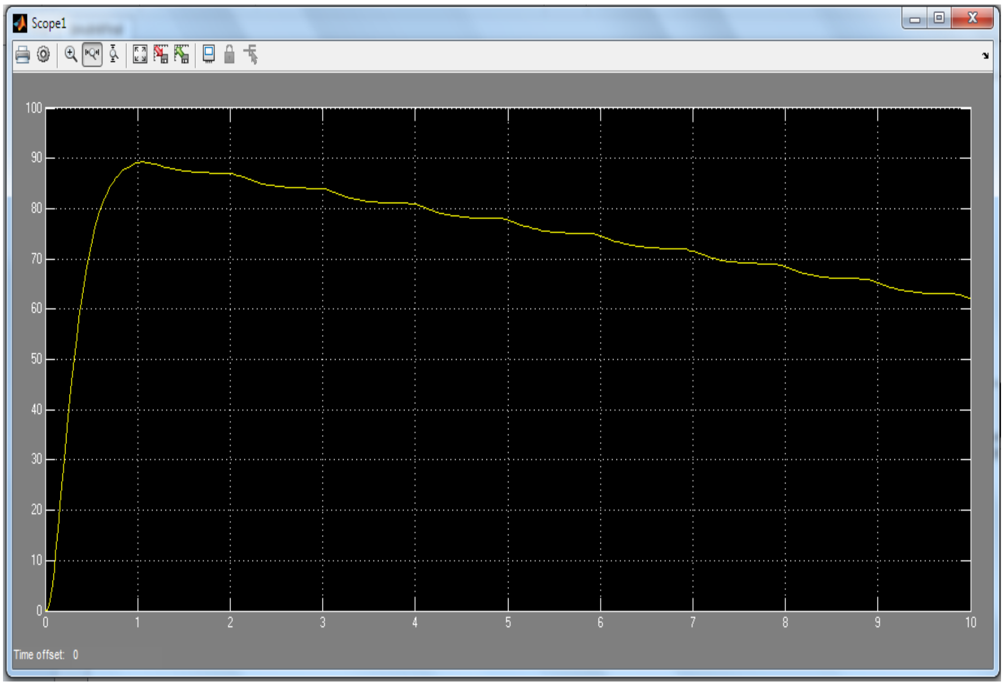


Figure 26: Step Response at Sample Time of 1 second

Desired Angle	Generated Angle (at 1 second sample time)
90	88.982
87	86.022
84	83.323
81	80.098
78	78.593
75	76.321
72	70.092
69	68.873
66	64.324
63	62.059

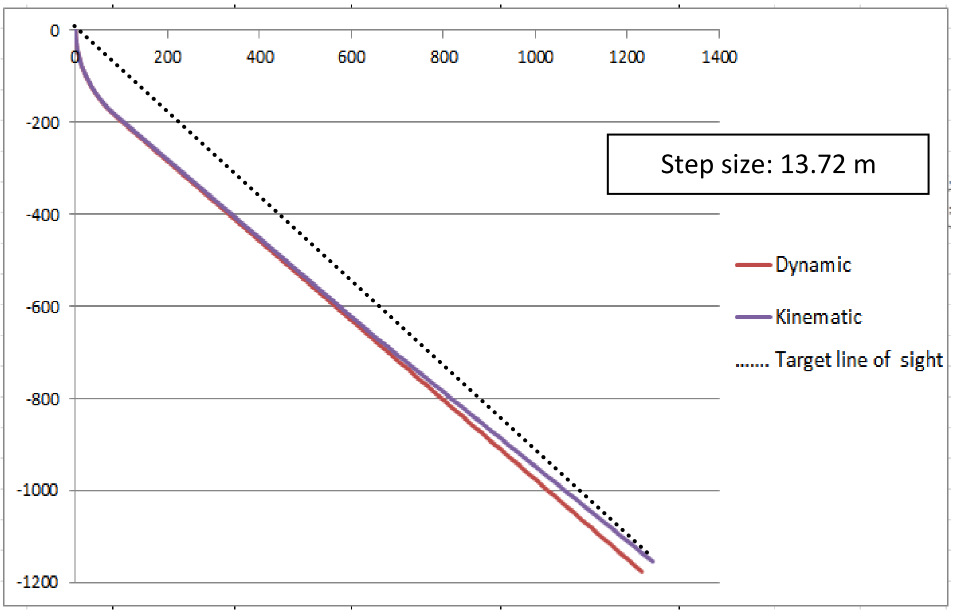
Table 4: Generated angles at sample time of 1 second

CONCLUSION AND RECOMMENDATIONS

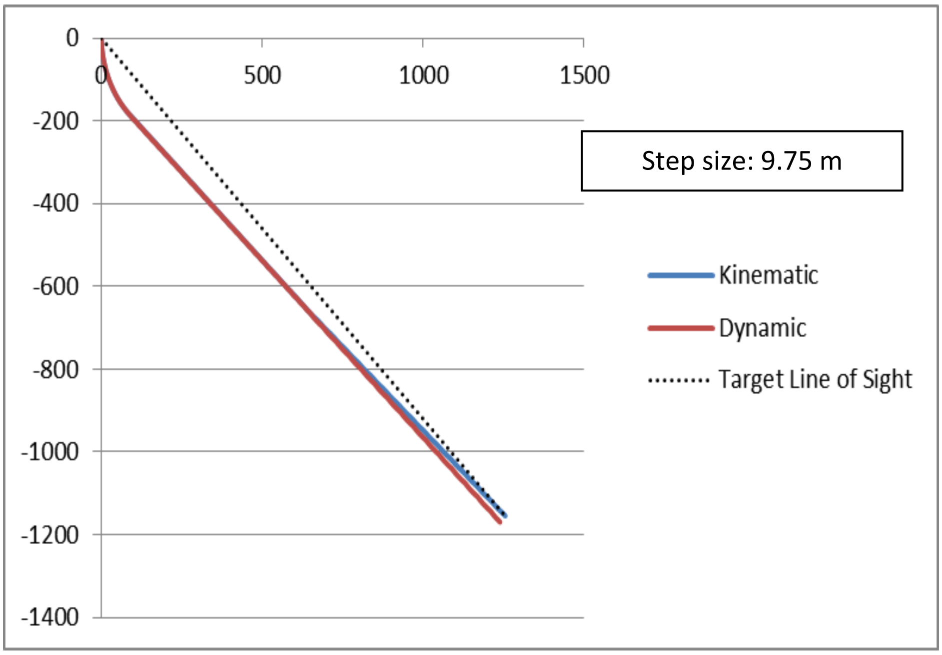
6.1 Conclusion

Figure 27 (a) to (c) shows the simulated well path using the suggested automatic control system from both kinematic and dynamic prediction. Regardless of the step size, although in some cases the bit does not exactly meet the position of the target, all well path generated through dynamic or kinematic prediction can reach the target. This demonstrates the ability of the proposed control system in guiding the bit movement along the correct path in order to hit the target. Besides, it is concluded that by the presented method, a digital simulation on drilling process can be performed to determine the best drilling parameter (length of drill pipe, bent angle etc.) for optimal control of directional drilling process.

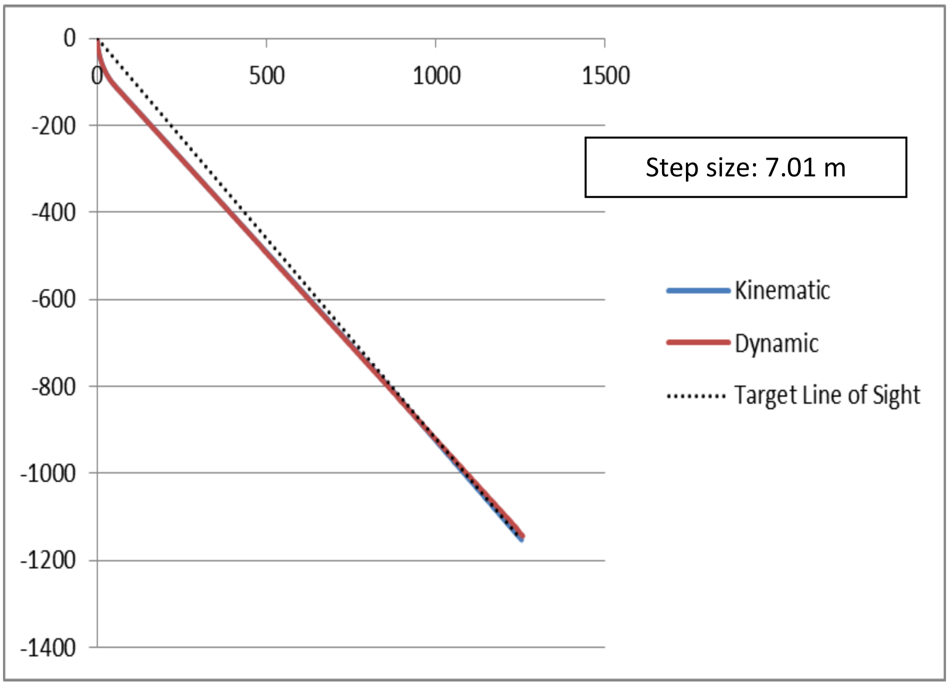
It is hoped that the completion of this project will give an idea on how to optimize the directional drilling process and minimizing the error. The automatic control system will helps in minimizing the human and operational error which will results in a more accurate well path being generated while drilling. This is very important especially when drilling in challenging environment (hard, high pressure and high temperature formation).



(a)



(b)



(c)

Figure 27: Generated Well Path for Three Different Step Size (Kinematic and Dynamic)

6.2 Recommendation

Below are few recommendations for future references:

1) Detail studies on dynamic system

As presented in section 5.3, the dynamic effects on the well path trajectory are not significant. This is because due to data limitation, only two dynamic systems are being considered in this projects which are torsional behavior of the drill string and gyro model of the MWD system. In real application, more dynamics should be considered to better evaluate the ability of the proposed control system. To further investigate the capacity of the control system, the following analysis should be taken into account:

i. Mechanical behavior of the well

ii. Dead zone between the formation and the bit

iii. Changing of geological formation while drilling

iv. Time delay in sending and receiving signals

v. Environmental noise

2) Selection of method for surveying bit movement.

In this project, the tangential method of surveying bit movement is used. This method uses the inclination and hole direction at the lower end of the course length to calculate a straight line representing the wellbore that passes through the lower end of the course length. Because the wellbore is assumed to be a straight line throughout the course length, it is the most inaccurate methods.

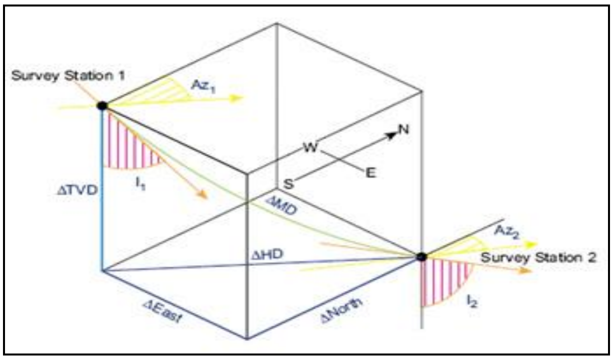


Figure 28: Tangential Method

Minimum curvature method of surveying bit movement is the most accurate of all method, uses the inclination and hole direction measured at the upper and lower ends of the course length to generate a smooth arc representing the well path. This method is the most current and popular and hence should be considered in the process of designing the control system so that the control system is more realistic and reliable.

3) Step size

In this project, the length of the drill pipe is considered as the step size to evaluate it effects on inclination and deviation of well path. Other than the length of the drill pipe, the distance of stabilizers on the bottom hole assembly can also be considered as the step size.

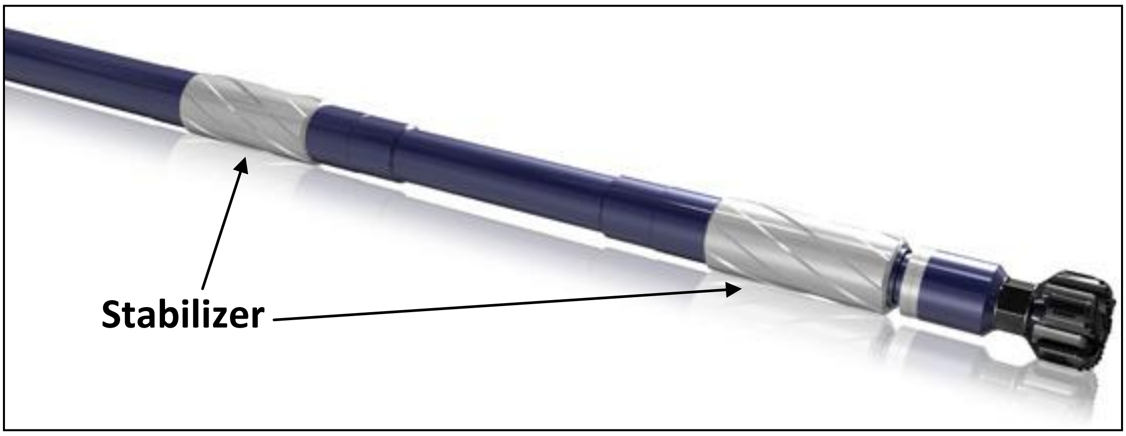


Figure 37: Stabilizer

Stabilizer is one of the main components used to control the hole inclination. Different distance and position of stabilizer will give different build or drop tendency of the bottom hole assembly and hence effect the wellpath inclination. So, analysis can be done to determine at what distance and position the stabilizer should be located in order to optimize directional drilling and minimizing the error. Figure 38 shows different configuration of BHA with different position of stabilizer that will give different build/drop/hold tendency.

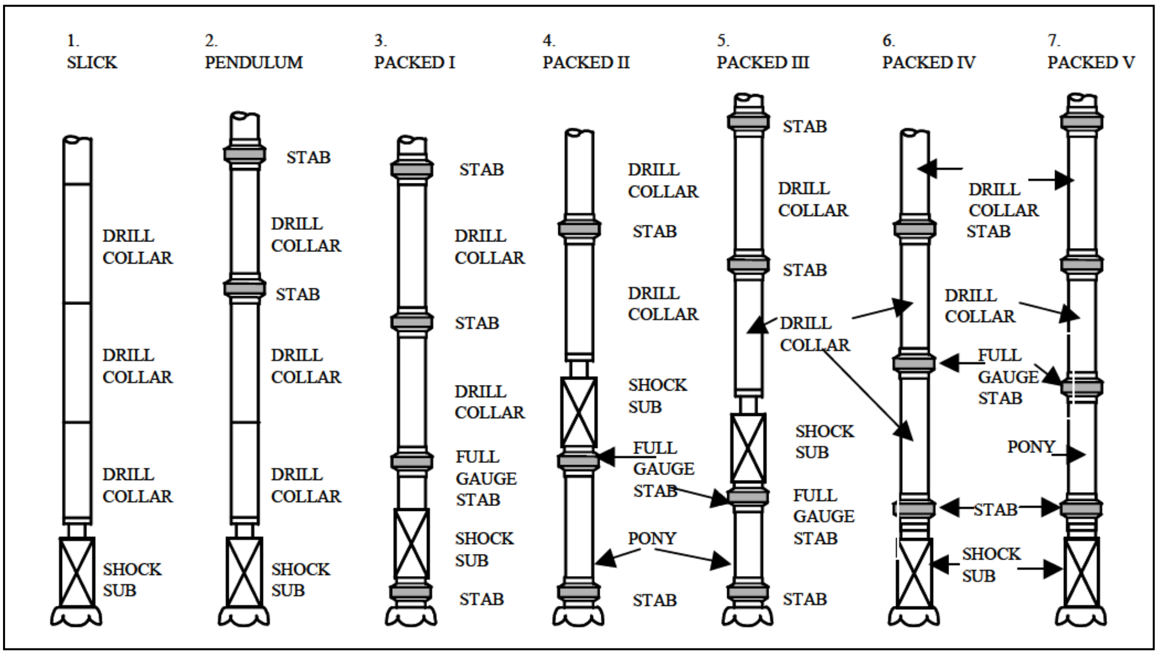


Figure 38: BHA configuration with different position of stabilizer

4) Actual Field Data

To evaluate the actual response of the suggested control system, the use of actual field data should be considered. The control system can then be run on drilling simulator to determine it abilities and limitation. Besides, by having actual field data, the control strategy can further be strengthen to suit it to the real application.

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APPENDIX 1

Gantt Chart and Proect Milestone

Activities	Week Number																											
	Final Year Project 1														Final Year Project 2													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	27	27	28
FYP Title Selection	🟦	🟦																										
Prelim. Research/Data Collection		🟦	🟦	🟦	🟦																							
Submission of Extended Proposal						🟥																						
Proposal Defence								🟦	🟦																			
Derive Systems's Dynamic Model										🟦	🟦	🟦																
Submission of Interim Draft Report													🟥															
Submission of Interim Report														🟥														
Simulation using Mathlab															🟦	🟦												
Design Control System																	🟦	🟦	🟦									
Optimize Control System																				🟦	🟦							
Submission of Progress Report																					🟥							
Simulation of Control System																						🟦	🟦	🟦	🟦	🟦		
Pre-SEDEX																								🟥				
Submission of Draft Final Report																									🟥			
Submission of Dissertation																										🟥		
Submission of Technical Paper																										🟥		
Viva																											🟥	
Submission of Project Dissetation																												🟥

🟦 Process

🟥 Project Milestone

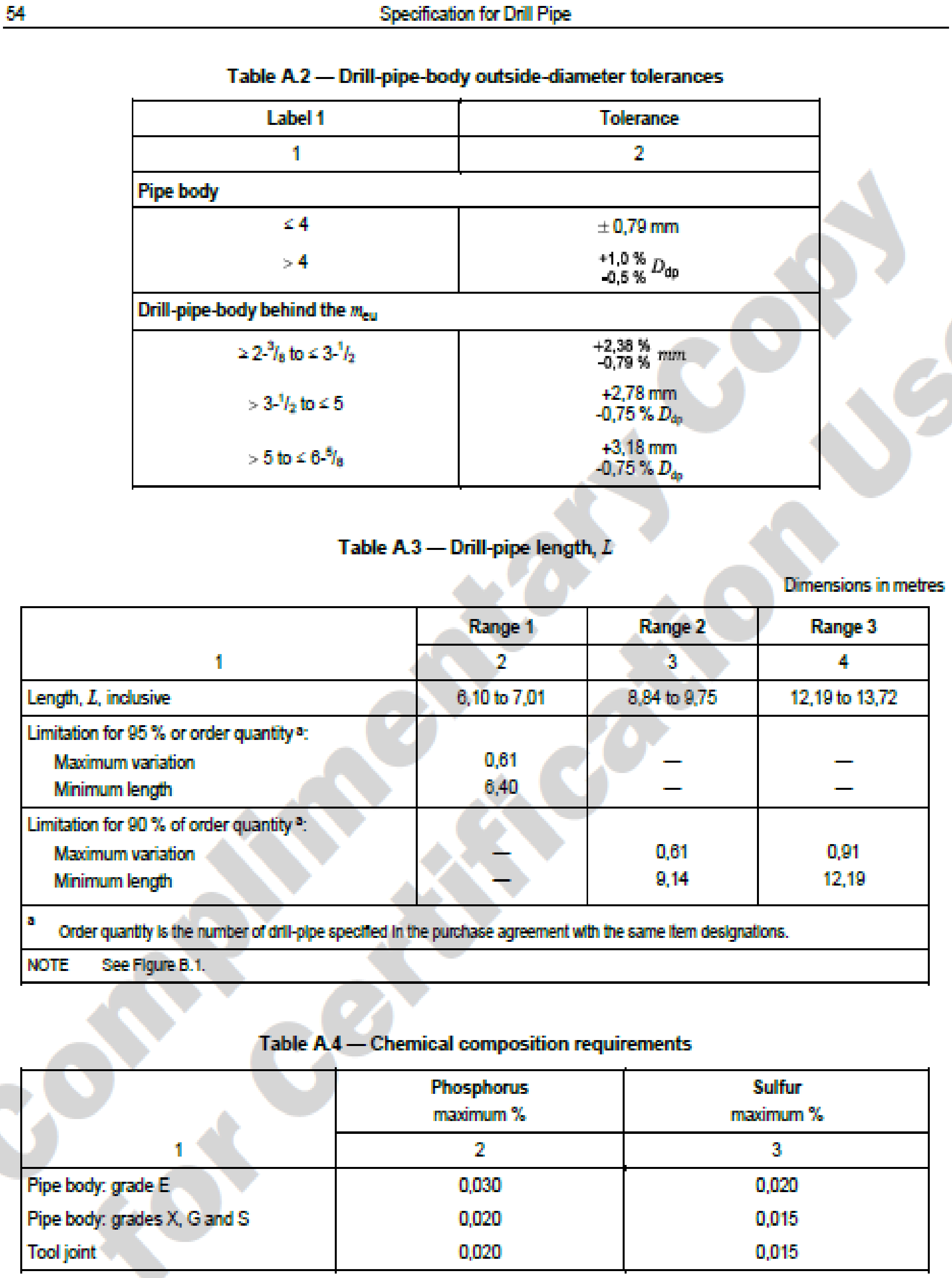
APPENDIX 2

Matlab Coding for Position and Direction Synthesis

```
x=0;
y=0;
i=1;
xf=1250;
yf=-1150;

dL=7.01;
f(1)=90;

if(y>yf)

    done = false
    while not(done)

    s=-atand((yf-y(i))/(xf-x(i)))

    if (f(i)>=s)
        x(i+1)=x(i)+(dL*cosd(f(i)-3))
        y(i+1)=y(i)-(dL*sind(f(i)-3))
        f(i+1)=-atand((y(i+1)-y(i))/(x(i+1)-x(i)))
        i=i+1

    else
        x(i+1)=x(i)+(dL*cosd(f(i)+3))
        y(i+1)=y(i)-(dL*sind(f(i)+3))
        f(i+1)=-atand((y(i+1)-y(i))/(x(i+1)-x(i)))
        i=i+1
    end

    if not(abs(xf-x(1))>abs(x(i)-x(1)))
     done =true

    end
    end
end

disp x
disp y
plot(x,y)
```

APPENDIX 3

API Specification for Drill Pipe (Length of Drill Pipe)



54 Specification for Drill Pipe

Table A.2 — Drill-pipe-body outside-diameter tolerances

Label 1	Tolerance
1	2
Pipe body	
≤ 4	± 0,79 mm
> 4	$^{+1,0\ \%}_{-0,5\ \%}\ D_{dp}$
Drill-pipe-body behind the m_{eu}	
≥ 2-$^3/_8$ to ≤ 3-$^1/_2$	$^{+2,38\ \%}_{-0,79\ \%}\ mm$
> 3-$^1/_2$ to ≤ 5	+2,78 mm -0,75 % D_{dp}
> 5 to ≤ 6-$^5/_8$	+3,18 mm -0,75 % D_{dp}

Table A.3 — Drill-pipe length, L

Dimensions in metres

	Range 1	Range 2	Range 3
1	2	3	4
Length, L, inclusive	6,10 to 7,01	8,84 to 9,75	12,19 to 13,72
Limitation for 95 % or order quantity [a]:			
Maximum variation	0,61	—	—
Minimum length	6,40	—	—
Limitation for 90 % of order quantity [a]:			
Maximum variation	—	0,61	0,91
Minimum length	—	9,14	12,19

[a] Order quantity is the number of drill-pipe specified in the purchase agreement with the same item designations.

NOTE See Figure B.1.

Table A.4 — Chemical composition requirements

	Phosphorus maximum %	Sulfur maximum %
1	2	3
Pipe body: grade E	0,030	0,020
Pipe body: grades X, G and S	0,020	0,015
Tool joint	0,020	0,015