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LONGE RANGE MAGNETIC LOCALIZATION SYSTEM

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Paper presents long range magnetic position estimation system which evaluates mutual position between transmitter and receiver in applications where other methods are not available. System is designed for deep subsurface localization between transmitter and receiver. The localization is based on excitation of the coils in transmitter with the known current pattern and evaluation of this response on the receiver. The transmitter consists of a set of two specially designed coils (axial and radial coil or two axial coils). The coils are optimized to provide maximal magnetic moment from available battery source and also meet the dimension constrains. The transmitter excites the coils consecutively with predefined current pattern (number of current pulses of known length and amplitude). The magnetic response of the excitation is recorded and evaluated on the receiver side by two magnetometers.

Keywords: magnetic, position estimation

1 INTRODUCTION

Subsurface localization is a challenging task since it is impossible to receive GPS signal and other radio methods are available only on a very limited range. The only available position estimation system is dead reckoning using inertial navigation system. This method suffers from integrating error which accumulates with time and therefore the precise navigation is limited with the time and also distance. Also high precise inertial measurement unit is extremely expensive also bulky.

Horizontal underground drilling is special case of object localization. Operators need to know exact position of the drill head with respect to the surface structures. For long drilling jobs where the location of entry point is known accurately, very precise optical gyros are used. Even thou the final length of the job is limited to (2km) with dead reckoning accuracy of ±2.5 m.

In case of extra long drilling jobs it is necessary to start two separate jobs from either sides due to the torque limitations. Then it is necessary to meet these two drill heads in the middle to create single tubular hole. Therefore the mutual localization between both drill heads is strongly important. The accuracy at the meeting point has to be in orders of centimetres.

2 THEORETICAL BACKGROUND

In order to be able to detect the position of the transmitter, magnetic field with high amplitude has to be generated. The transmitter consists of two high current coils. To simplify the situation the coil is taken as current loop for far field approximation. Since the magnetic field generated by a solenoid has rotational symmetry, the far field can be described using radial and tangential components from (1) and (2) [1]:

$$B_\phi = \frac{2\mu_0 M \cos\phi}{4\pi r^3} \tag{1}$$

$$B_r = \frac{\mu_0 M \sin\phi}{4\pi r^3} \tag{2}$$

where: B_ϕ - is tangential magnetic field component, B_r - is radial magnetic field component, M – is magnetic moment of the coil, r – is distance from the coil, ϕ – is angle between the point in space in distance r and solenoid axis. Magnetic moment of the coil is calculated as

$$M = NIS \tag{3}$$

where: N – is number of turns, I – is current flowing thru the coil, S – is area of a single turn.

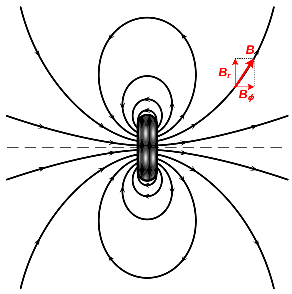

Fig. 1. Current loop magnetic field model

From above it is clear that dynamic range of the measurement has to be wide enough to cover range up to 20 m and thus the coil current has to be adjustable in order to avoid any over range of the sensing part. Current of 15 A causes magnetic field of 120 μT in the distance of 0.5 m from the coil while in the distance of 20 m the field intensity drops below 2 nT. Magnetic field intensity is decreasing with the cube of the distance to the source which strongly limits the detectable range of such system. The accuracy of the magnetometer in receiver is 0.2 nT.

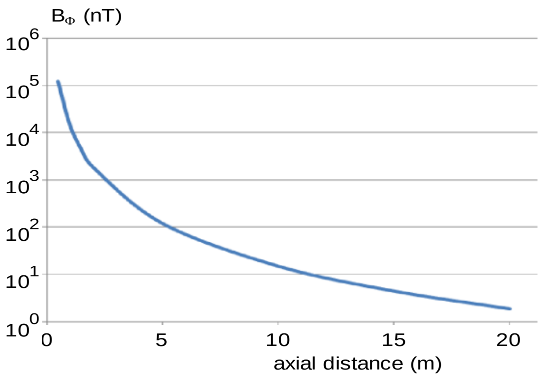

Fig. 2. Tangential components of the solenoid on the axis

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3 SYSTEM DESCRIPTION

Magnetic field transmitter consists of two coils (radial and axial coil or two identical axial coils might be used). In order to achieve maximal magnetic moment of the coils with respect to the space available and battery constrains.

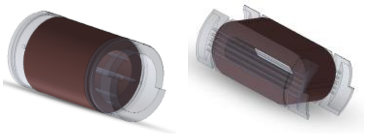

Fig. 3. Radial and axial coils

The whole system is enclosed in the set of two massive nonmagnetic stainless steel pipes which are used to transfer the torque to drill head. The length of nonmagnetic drill chain part is 2.2 m. The rest of the drill string is made from magnetic steel alloy. The stainless steel alloy is from nonmagnetic AISI 316 (μ_r = 1.005). The diameter of these pipes is 136 mm for inner pipe and 170 mm diameter for outer pipe. The position of the coil with respect to electronic unit is known, fixed and stable. Since the coil needs to fit within the inner cavity the maximum diameter of the coil is 120 mm. The coil design has to be optimized with respect to the maximal achievable magnetic moment with given battery voltage, wire resistance, length and diameter. After optimization the coil has 1007 turns, resistance of 3.1 Ohm, and average diameter of 80 mm and length of 140 mm. The available battery voltage is 48 V and thus the maximal achievable current is 15.5 A. Measured maximal current was 15 A due to the drop on the switching circuit and connections.

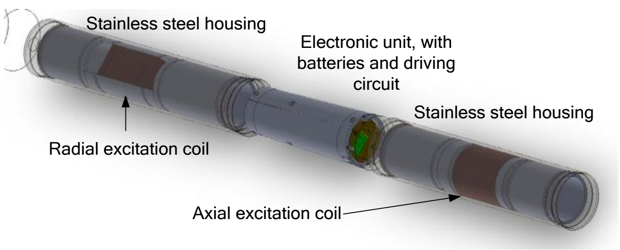

Fig. 4. Coil unit (shown with two axial coils)

Coil current is controlled by a full H bridge circuitry enabling both current polarities as well as full amplitude control. In order to remove hard iron effect of the surrounding material as well as ambient magnetic fields and to increase magnetic field step it is necessary to use current of both polarities. The maximal value of the excitation current is 30 A, peak-to-peak. Coils are excited consecutively with several current pulses of both polarities and also the responses on magnetometer side are evaluated separately

Unit with two high accurate magnetometers is used on the receiver side. The tri-axial fluxgate magnetometer module has a range of ±100 μT with resolution of less than 0.2 nT (including processing electronics). Since there is a high possibility of hard metal influencing from magnetic drill chain components there is a compensation coil winded around the magnetometer.

This coil is used to compensate any field in drill chain axial direction. In some cases the field from magnetic components is that strong that it causes magnetometer over range problem and thus makes measurement impossible. The compensation coil compensates for this hard iron effect and returns the value of axial field into measurable range.

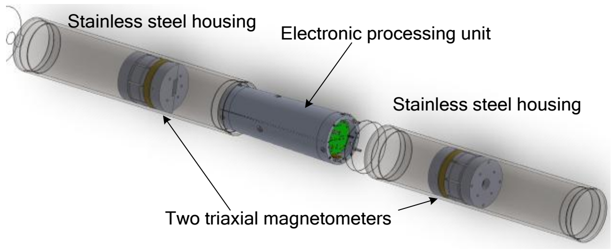

Fig. 5. Magnetometer unit

The electronic unit contains also a three axis accelerometer to estimate Roll and Pitch of the whole system. The six channel processing electronics on the magnetometer side simultaneously samples data from the magnetometer, data are processed by 24 bit ADC.

Yaw angle of both units is also essential for data processing. A part of the drill string is also laser ring gyro which is used for dead reckoning and navigation of the unit during standard drilling job. This gyro provides accurate information of the yaw angle for each unit. The accuracy of the yaw information is 0.05°. This is much better than accuracy of accelerometer in roll and pitch estimation (0.2 deg).

Since the coil excitation period is quite short because of limited battery capacity both units has to be synchronized together in order to start sampling data at a right time and with correct phase with respect to excitation signal. The duration of the drilling job might be between several hours up to several days (eventually weeks) the time synchronization between units is quite complicated. Both systems are synchronized by a magnetic pattern transmitted by the axial coil. Excitation sequence consists of three phases:

- Synchronization pattern
- First coil excitation period
- Second coil excitation period

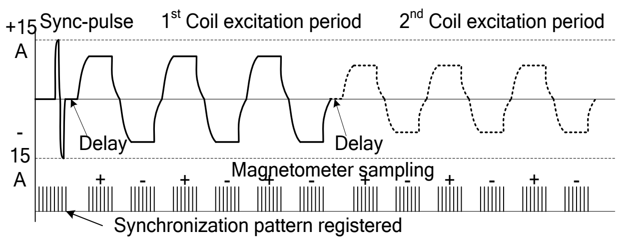

Fig. 6. Excitation sequence

Before the excitation sequence starts, operator switches the magnetometer units into listening mode where all coming magnetometer data are processes by a pattern convolution filter and unit is looking for the known pattern in magnetometer signal (two pulses of opposite polarity 50 ms each, maximal current ±15 A on the transmitting coil). The coil excitation starts defined time after this synchronization pulse. The coil excitation sequence consists of known number of pulses with known adjustable current amplitude and also known length.

4 DATA PROCESSING

After the excitation sequence is over following data are available for processing:

Coil excitation unit

- Ψ_C *coil unit yaw*
- ϑ_C *coil unit pitch*
- φ_C *coil unit roll*
- I_1 *First coil excitation current [$A_{p\text{-}p}$]*
- I_2 *Second coil excitation current[$A_{p\text{-}p}$]*

Magnetometer unit

- Ψ_M *magnetometer unit yaw*
- ϑ_M *magnetometer unit pitch*
- φ_M *magnetometer unit roll*
- $B_{1\text{-}1}$ *Magnetic field vector of differences measured by Magnetometer 1 for first coil excitation period [$nT_{p\text{-}p}$]*
- $B_{1\text{-}2}$ *Magnetic field vector of differences measured by Magnetometer 1 for second coil excitation period [$nT_{p\text{-}p}$]*
- $B_{2\text{-}1}$ *Magnetic field vector of differences measured by Magnetometer 2 for first coil excitation period [$nT_{p\text{-}p}$]*
- $B_{2\text{-}2}$ *Magnetic field vector of differences measured by Magnetometer 2 for second coil excitation period [$nT_{p\text{-}p}$]*

First step in data processing is transformation of magnetic vectors $\boldsymbol{B}$ from magnetometer body coordinate frame to reference navigational frame (horizontally leveled north aligned).

$$\boldsymbol{B}' = [\boldsymbol{A}_{\Psi M}]^{-1}[\boldsymbol{B}_{\theta M}]^{-1}[\boldsymbol{D}_{\varphi M}]^{-1} \times \boldsymbol{B} \qquad (4)$$

Where:

$\boldsymbol{A}_{\Psi M}$ is magnetometer yaw rotational matrix
$\boldsymbol{B}_{\theta M}$ is magnetometer pitch rotational matrix
$\boldsymbol{D}_{\varphi M}$ is magnetometer roll rotational matrix

In the second step the magnetic vector is transformed to the coil unit body reference frame (index C means coil unit).

$$\boldsymbol{B}'' = [\boldsymbol{D}_{\varphi C}][\boldsymbol{B}_{\theta C}][\boldsymbol{A}_{\Psi C}] \times \boldsymbol{B}' \qquad (5)$$

The iteration process [2] uses adjustable magnetic dipole model to find a point in space which corresponds to the measured magnetic field vector. Since magnetic dipole orientation corresponds to the coil unit orientation data processing is done in coil unit reference frame. There is a result for every measured magnetic field vector. The result is given by spatial Cartesian coordinates *x,y,z* describing point in the space with respect to the coil unit body reference frame. Such result is then transformed to navigational frame and presented to operator in graphical form fig 7.

$$\boldsymbol{R}' = [\boldsymbol{A}_{\Psi C}]^{-1}[\boldsymbol{B}_{\theta C}]^{-1}[\boldsymbol{D}_{\varphi C}]^{-1} \times \boldsymbol{R} \qquad (6)$$

There are four results in total. The result of the iteration algorithm is not unique. There are always at least two solutions for every magnetic field vector processed. Two results are always point symmetrical. The results from the known geometry and known distance between magnetometers and coils there is only one unique combination of results which corresponds to the real geometry.

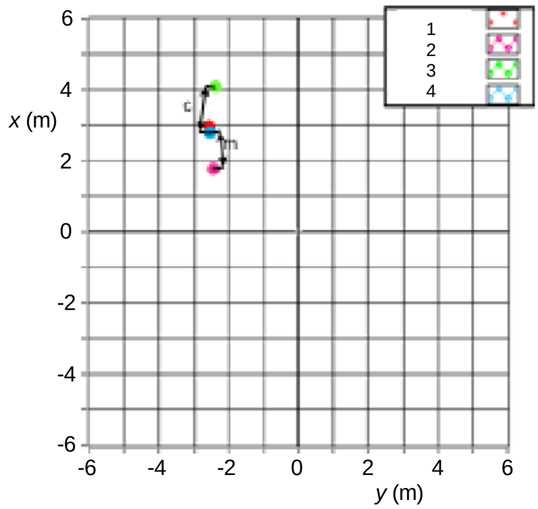

Fig. 7. Operators results screen – top view: : 1 – MAG1 axial, 2 – MAG 2 axial, 3 – MAG1 radial, 4 – MAG2 radial

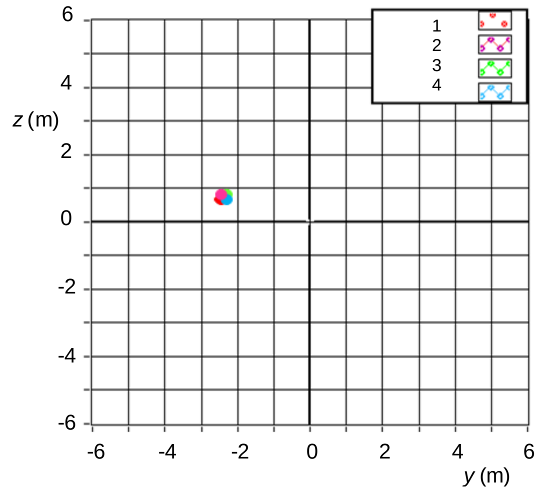

Fig. 8. Operators results screen – cross-sectional view: 1 – MAG1, axial, 2 – MAG 2 axial, 3 – MAG1 radial, 4 – MAG2 radial

If the results are compensated for distance between magnetometers and distance of the coils we will get a single point solution which gives unique point with coordinates *x,y,z* Fig 9. This point corresponds to the location of the magnetometer unit with respect to coil excitation unit under the ground.

First limitation of the system is maximal distance where the system is able to reliably recognize synchronization pattern. Improved triggering pattern is able to be recognized by the magnetometer unit on the distance up to

20 m from the coil system (axial position). The measurement distance is limited by following facts:

- *signal to noise ratio (12dB at 20 m)*
- *synchronization ability 20 m max*

The measuring accuracy is limited by:

- *signal to noise ratio*
- *mutual position of the coil and magnetometer*
- *accuracy of the yaw, pitch and roll estimation*

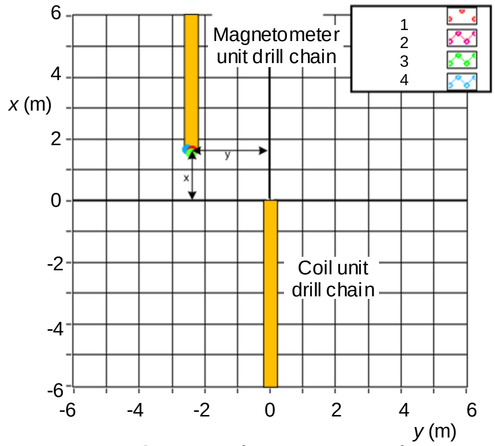

Fig. 9. Operators results screen after compensation formagnetometer and coil offsets: : 1 – MAG1 axial, 2 – MAG 2 axial, 3 – MAG1 radial, 4 – MAG2 radial

5 RESULTS AND DISCUSSION

The approximate error of the system was verified in several measurements points resulting in Tab.1. The estimation of unit yaw, roll & pitch is critical for accuracy in longer distances. At 10 m error in roll of 1° might cause error in calculated z and y coordinate of 0.8 m. Therefore a special accelerometer calibration procedure was implemented. Accurate roll estimation is critical in case of radial coil and magnetometers. Axial coil is not influenced by the roll at all since it has roll symmetry.

Tab. 1. Estimated accuracy of the system

Distance [m]	Position error [m]
0.5m	0,15
2m	0.2
5m	0.4
10m	0.8
15m	1.4

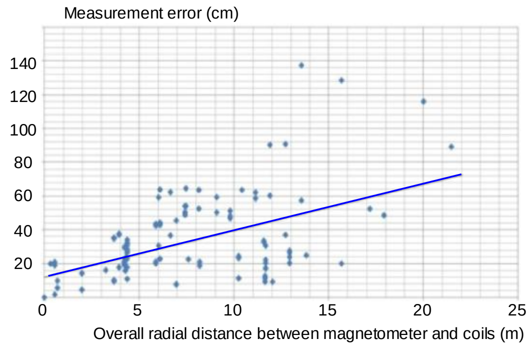

Fig. 10. Estimated error

6 CONCLUSION

The developed underground magnetic ranging system can be used up to distance of 15 m. The measurement results were achieved during test with two real drill chains moved by crane. The measurement accuracy steeply drops with increasing distance due to SNR as well as roll and pitch accuracy. For longer distances system is used for rough estimation of the position.

The advantage is that the closer the systems are the more accurate results are achieved. In very close distance bellow 0.5 m the effect of magnetic parts in second system has to be taken into account and thus even in very close positions the accuracy will not be better than 0.15 m. The results achieved so far show the necessity to increase roll measurement accuracy because it strongly influences results. Coil unit with two axial, roll independent, coils was introduced and is going to be tested in near future. Also improved single roll accelerometer calibration procedure will be implemented and tested in order to reduce part of the error caused by roll and pitch measurement.

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