Innovative Downhole Tools for Cause Study and Maintenance in Deep Geothermal Energy

Benedict Holbein, Stefan Dietze, Jörg Isele, Luigi Spatafora, Friedrich Wiegel, Veit Hagenmeyer

Institute for Applied Computer Science (IAI), Karlsruher Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen

Abstract

The potential of geothermal energy is undoubted. While shallow geothermal energy can be used with minimal risk but with small energy production, deep geothermal energy has still some barriers to overcome. Among high drilling costs, production rates below the expected range make it hard to compete for deep geothermal energy with other energy sources. Additionally, the risks of induced seismic events or uncontrolled water leaks leading to ground lifting obstruct the acceptance and promotion of this technology.

With a long history in developing remote-handling tools e.g. for inspection and maintenance of pipes and sewers, the Institute for Applied Computer Science (IAI) started in 2010 with the work on specialized tools for deep geothermal boreholes. The overall target of this project is to provide suitable tools for studying geothermal boreholes, especially with regard to faults and their effects on efficiency and safety of geothermal projects as well as maintenance to recover geothermal boreholes showing respective defects. Since the constraints downhole are challenging, the technical solutions require a high grade of innovation and specialization and are therefore expensive. In order to realize solutions with high quality embodied in affordable tools, a system platform approach is pursued. This approach allows reusing and advancement of basic tool components for a wide range of different applications.

When discovering new spaces, it is a human and scientific desire to get visual impressions from the unknown environment. Therefore, following the example of pictures from the Mars, the first functional example of the system platform for downhole tools, is a video inspection system called GeoKam. Besides the obvious wish for a literal insight in deep geothermal boreholes, the video application provides several advantages. Since it is a complex operation to record, process and transfer live-videos from deep geothermal boreholes, the device shows the performance of the system platform regarding the main challenges of downhole operation: high temperatures, high pressures, small spaces and long distance tool handling and data transfer via wirelines. Beyond that, a live downhole video stream is a necessary precondition for maintenance operations as leakage repair.

Introduction

Headlines about earth quakes, houses damaging ground lifts and after-shocks caused by geothermal projects underline the rejection which geothermal energy faces [1][2][3]. And these lines are not unjustified, because there are many 'bad' examples of geothermal projects which cause a lot of damage. Not to mention the less spectacular cases, without huge economic damage for third parties, in which the energy production is strongly decreased or even stopped and therefore result in financial losses for investors and operators [4][5].

Experts in geothermal energy do not grow tired of proclaiming the large unused potential of geothermal energy, which can only be used when the major problems are overcome.

Based on the statements of stakeholders these are: high drilling costs, unprofessional drilling, technical and seismic risks as well as unexpected risks [6]. Besides the drilling costs, which require innovations and a steady learning curve in drilling technologies, the named risks could be strongly reduced with adequate methods for cause study and maintenance in geothermal boreholes – or in other words: with suitable tools for quality management including inspection and repair operations. Additionally, clear information about the causes of problematic incidents and trustable measures to fix them would also increase the public acceptance for geothermal energy.

System platform for downhole tools

Regarding the challenging constraints for operation in deep boreholes, it is advantageous if a stock of basic components is available, thus the developing effort can be focused on an innovative functional device e.g. measurement sensor or external actuator. Figure 1 illustrates the central idea of the system platform approach for downhole tools.

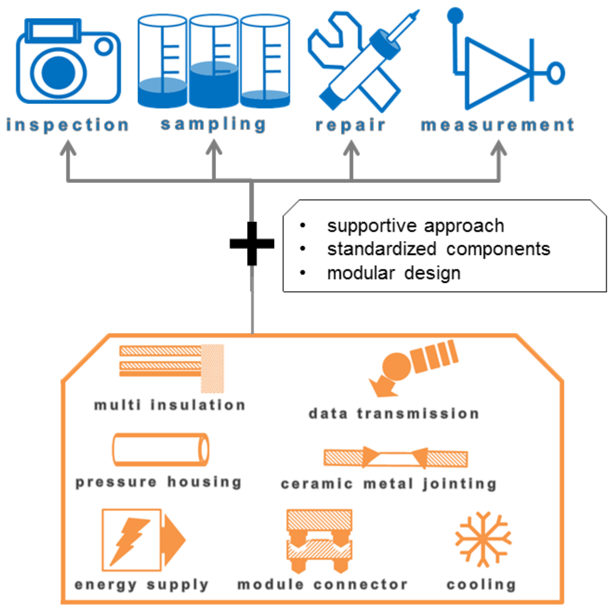

Fig. 1: Modular system platform scheme for downhole tools.

As indicated there are four basic operation categories which shall be targeted to provide a wide-spread investigation and interaction range in deep geothermal boreholes. The orange box shows an excerpt of components which are needed for every downhole operation and are therefore defined as basic components for the system platform [7].

Constraints for the design of components

Generally spoken, the constraints for operations inside deep geothermal boreholes are challenging in different ways. In operation depths of up to 5.000 m, the deepest casing diameter is usually not bigger than 7 inch, approximately 180 mm. At the same time, there is a high hydrostatic pressure of up to 600 bar for which sufficient housing wall thicknesses are required. Hence, the actual design space for functional devices is small. A second challenge is the surrounding fluid or thermal water which in most cases is highly saline and corrosive. The corrosion effect is even stronger with increased temperature. Therefore special non-corrosive alloys have to be used for external components which also provide a high strength to minimize the necessary wall thickness. Of course the high strength is a challenge for manufacturing.

Another constraint which is unavoidable, since it represents the target item of geothermal energy, is the temperature. Borehole temperatures of over 200 °C also appear in Germany, while some boreholes in Turkey, Iceland or Italy reach temperatures of over 350 °C. This causes high thermo-mechanical stresses for external components but most of all it is problematic for the usage of electronic components. Especially complex operations require a certain computational power, e.g. the downhole processing of pictures to improve the transfer rate to the surface via wirelines, which have limited data transfer capacities. In order to make a wide range of electronics usable, solutions for cooling and heat insulation have also to be provided by the system platform.

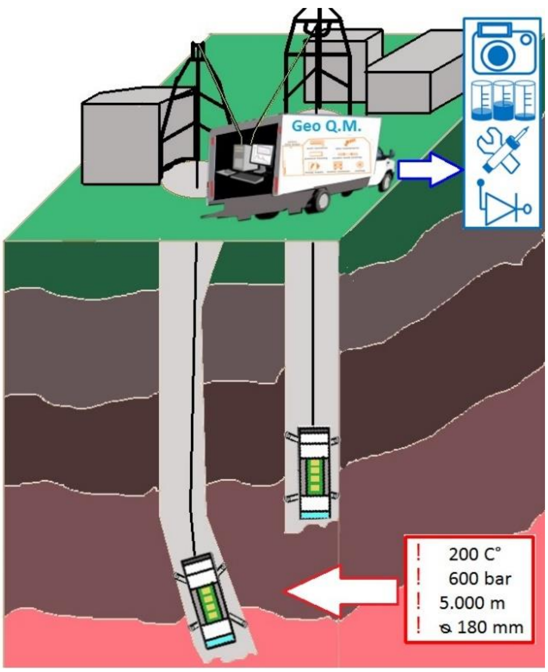

Fig. 2: Quality management with downhole tool operations in great depth

Applications in deep geothermal boreholes

As explained above, different operation categories are targeted to generate widespread information and provide widespread interaction possibilities. This covers monitoring of chemical and physical downhole parameters, long-term logging of slowly changing properties or induced tracers for flow tests, inspections e.g. using a camera system, sample recovery or repair operations.

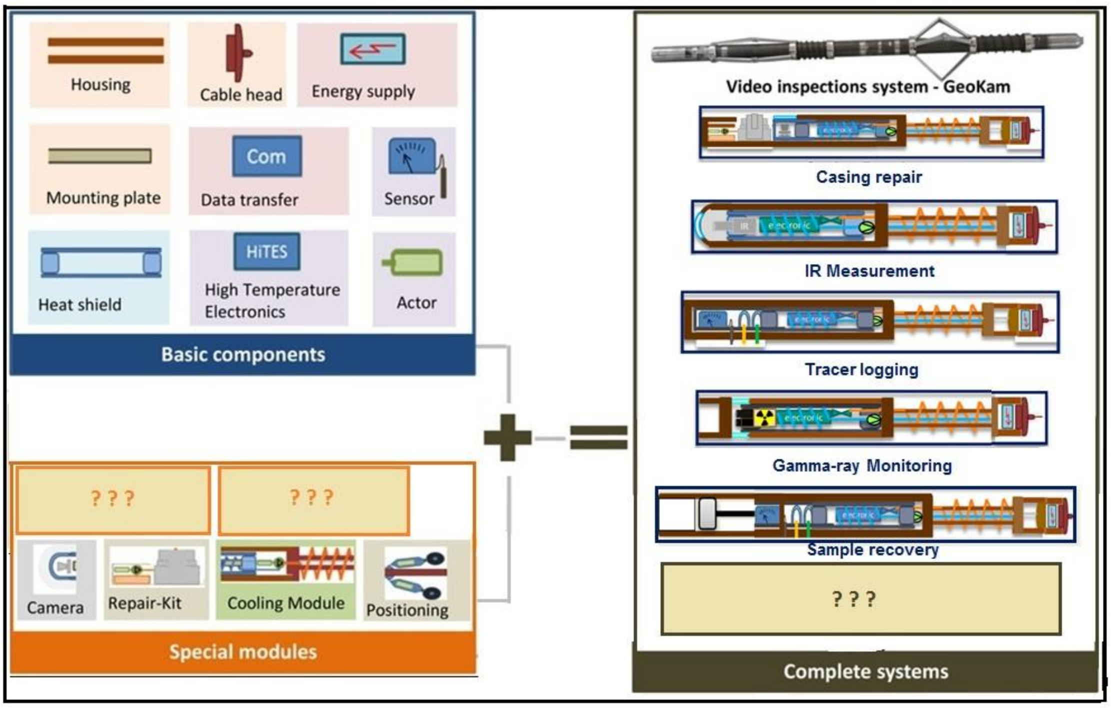

Fig. 3: Basic components and functional modules build complete systems for various applications.

Some example for interesting downhole applications are shown in figure 3. It also points out how many components are repeatedly used with the system platform approach. By reducing the engineering effort for new tools to a small number of elements, the development of new tools is promoted.

Live video inspection system GeoKam

A live video stream from inside boreholes provides several possibilities. Firstly it gives a visual insight to detect pluggings and obstacles for other tools or to localize defects in boreholes casings as leakages which can be responsible for uncontrolled water outflows. Secondly it gives the opportunity to interact instantly with an adequate actuator. Additionally, a camera to identify, loca-lize and focus defects in real-time is the necessary pre-condition for any repair or maintenance action.

GeoKam is developed within a joint project, funded by the Federal Ministry for Economic Affairs and Energy BMWi under the number 0325580. The project partners Karlsruhe Institute of Technology, Fraunhofer Heinrich-Hertz-Institute, Fraunhofer IKTS, the inspection service company brg and Stadtwerke München defined together the constraints for the GeoKam development:

- Housing outer diameter: 95 mm (~ 3 ¾ Inch)
- Suitable for open-hole diameter: 215 mm (~ 8 ½ Inch)
- High quality images: Light system, lenses
- Wide angle of view: 360°, axial & radial view
- Robust design: Materials, electronics, cooling system
- Max. hydrostatic external pressure: 48 MPa (~4 km depth)
- Max. ambient temperature: 165 °C (~ 2-3 hours operation time)

Video specifications and lighting

Since the data transfer rate via wirelines is limited, the GeoKam needs a downhole CPU to process the pictures and provide a sufficient frame rate of more than 10 frames per second with a resolution about 752x480 pixels. Currently 10 fps are reached reliably and the frame rate will be further increased. For a high depth of focus, apertures and focuses can be remotely controlled. Additionally GeoKam has a lighting system, consisting of different levels of robust high temperature LEDs which are separately controllable and dimmable. This provides sufficient conditions of illumination for sharp and clear pictures.

Fig. 4: GeoKam prototype test, in the geothermal test-hall at the IAI.

Modular mechanical structure and heat insulation

The modular principle of the system platform for borehole tools is realized with several radial layers. The outer layer is the pressure resistant housing, secondly a Dewar flask with Multi-Layer Insulation works as heat insulation and accommodates the cameras and electronics. The mounting body of the electronics is thermally connected to a Phase-Change-Material storage at the upper end of the tool via heat-pipes. This design protects the sensitive electronics – especially camera chips and controllers – from overheating during the operations.

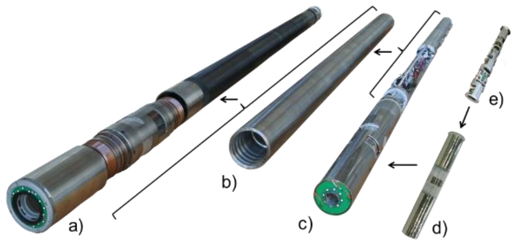

Fig. 5: a) pressure housing components, b) steel Dewar,
c) internal components, d) camera unit and framed Glass Dewar.

In the area of the cameras for front and radial view transparent windows are required. Therefore the vacuum insulation is realized with a Glas Dewar and the housing section has ceramic windows. For the fabrication and connection of the magnesium spinel ceramics with the super-alloy Inconel 718, a special procedure is developed with the company Ceramtec. Especially the radial windows represent a challenge under the high pressure and temperature conditions.

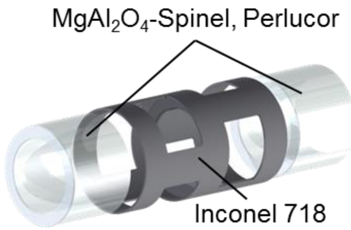

Fig. 6: Configuration of the housing segment with radial windows.

For a 360° view, under the restriction from video service operators that the picture does not rotate and regarding the rotation angular of cable harnesses, a mirror-camera configuration with 60° rotation and several radial windows was realized. By switching between the cameras every spot in 360° can be focused without having to rotate backwards (figure 7).

This feature is made possible by using Selective Laser Melting SLM for the fabrication of the camera unit frame components. The frame is also much lighter and the fabrication is faster and cheaper compared to a previous version manufactured by cutting. The SLM fabrication has also been used for other components where free-forms are advantageous, as e.g. the external lighting frames or heat exchanger [8].

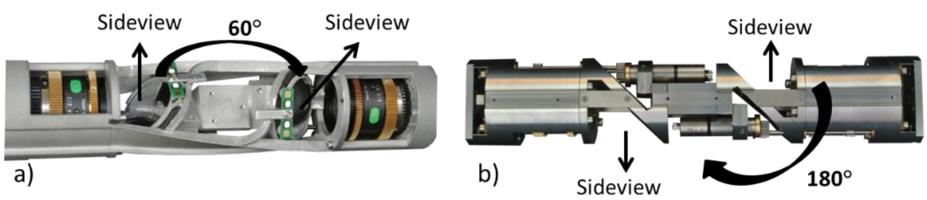

Fig. 7: camera unit fabricated using a) SLM and b) cutting.

Flexible High Temperature Embedded System

Hardware

The High Temperature Embedded System (HiTES) is developed for a permanent electrically supplied borehole tool for 165 °C (figure 8). The hardware of the HiTES board consists of a Spartan 6 FPGA as well as additional periphery as 4 MByte SRAM, 4 MByte EEPROM, 100 Mbit/s Ethernet Dual-Phy, DAC, ADC etc. For connecting cameras of the tool and various sensors and actuators, the system provides different interfaces as CAN, I²C, LVDS and Ethernet. An FPGA provides a maximum of flexibility, because through embedding respectively programming of further hardware modules (IP-Cores, intellectual property core) in the FPGA, additional interfaces for measurement devices in the cargo area are realizable.

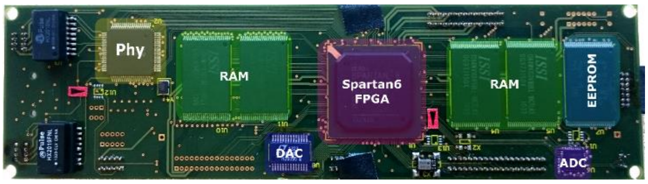

Fig. 8: Overview HiTES board.

The high data transfer of FPGAs allows the direct connection of digital cameras, the implementation of independent network ports and the bundling and transfer of contents to the surface.

Due to the high complexity of single IP-cores as image capturing and processing units, softcore Leon3 processor and the powerline modem, the strategy to split up the functionality into two HiTES boards is pursued at the moment (figure 9). The HiTES-Ctrl board is responsible for controlling the tool periphery and image capturing and provides all required functionalities for these tasks. The HiTES-modem board contains the OFDM powerline modem and takes care of the adjustment of data for the given transfer channel. The exchange of data between the two boards within the tool is done via 8-bit parallel port, whereby an Ethernet based communication is targeted. The schematic structure of the system within the borehole tool is illustrated in figure 9.

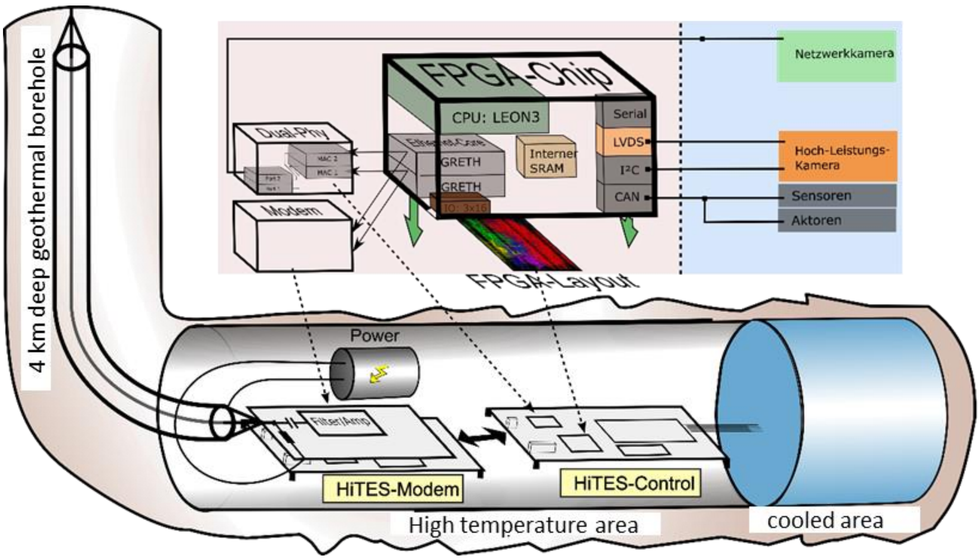

Fig. 9: Split up of high temperature tool area system.

Data transfer as well as high voltage supply of the tool is done via a robust coaxial cable (powerline) with 4.000 m length. The used OFDM modem was developed by Fraunhofer Heinrich Hertz Institute (HHI) within the GeoKam project and provides a gross data rate of 7.8 Mbit/s. As the winch cable shows a frequency dependent dumping, the available bandwidth is optimally used by the OFDM modulation in combination with water filling.

For increasing the failure tolerance of the transfer system the data is encoded with Reed-Solomon-Code. The used RS(156, 116, 41) code is a shortened code on GF(2^8) and can correct up to 20 symbols or in the optimal case up to 160 Bit. The target was to shift the given SNR of 20 dB at the receiver from 5·10E-4 to under 1·10E-10 (figure 10). This could be reached with the integrated channel encoder. However the necessary measurement of the Bit failure rate on the real wireline is still lacking. The used channel encoder is developed as VHDL and realized as IP-core.

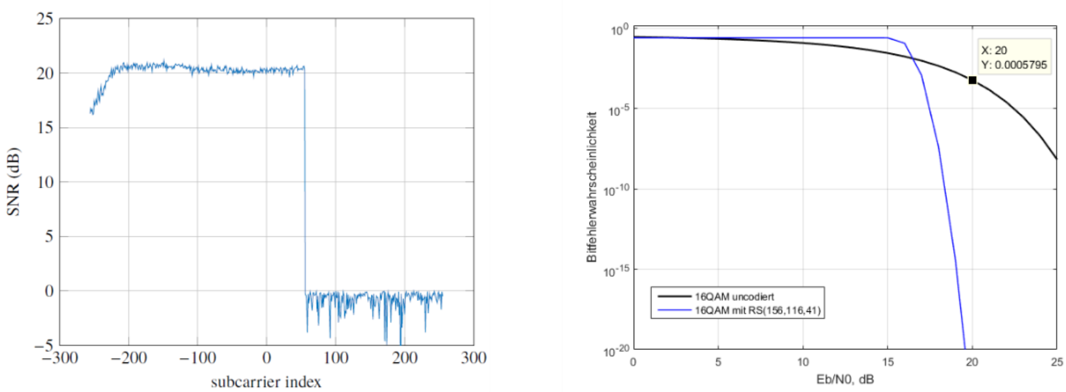

Fig. 10: SNR at the receiver and Bit failure probability with and without channel encoding.

Firmware and soft-cores

As processor system the open-source soft-core CPU Leon3 (32 Bit) from Aeroflex Gaisler is used, which contains many custom combinable soft-core standard components for the connection of SRAM, IO, I^2C, Ethernet etc. The internal AMBA-Bus (32 Bit) allows the CPU the access on it. Own soft-core components as data transfer, color space convertion, JPEG compression, OFDM modulators and demodulators, channel encoder are equipped with an AMBA interface respectively.

As basis for the firmware of the different Embedded Systems the real-time operating system eCos is used for comfortably realizing different control and regulation tasks with multi-tasking.

GeoGUI

The demodulation at the Host is done by an Embedded System with the same structure. This one sends an image flow and measurement values as UDP messages to the PC and receives commands for the tool from it.

The PC software GeoGUI consists of an engine which assigns a time stamp to all incoming data and forwards it to the data base, respectively to the visual user interface (GUI). Commands of the user are written into the data base or send via UPD. GeoGUI allows also the parallel playing of image sequences and measurement sequencesvalues during recording.

Conclusion

Geothermal energy has the potential to work as baseload supplier for electricity and heat in the energy system of the future and therefore support the overall target of the German energy transition. Unfortunately in its current state it is not competitive and faces strong antipathies due to technical risks and their consequences.

Suitable and most of all – for operators and science – available tools, which provide a high range of interaction and investigation possibilities within boreholes would be an essential progress towards an intensive usage of geothermal energy in the future.

An example for the cutting edge development of tools is the data transfer rate using long wirelines. The actual image refresh rate of the GeoKam is 10 images per second, while currently an improvement of the total system performance, minimizing of latencies as well as increasing of image refresh rates is worked out intensively. This is a unique feature for video inspections under the extreme surrounding conditions and will establish all new possibilities.

The presented system platform approach with its first functional tool for video inspection provides a promising approach towards a wider range of technical opportunities for cause study, efficiency improvement and maintenance – elements of a reliable quality management – in geothermal energy.

References

[1] Deckert, Ralf: *Folge fataler Bohrungen – Staufen gerät aus den Fugen (Eng. Staufen gets out of joint)*, March 09, 2015, www.stuttgarter-nachrichten.de, last accessed: June 07, 2016.

[2] Kulish, N., Glanz, J.: *German Geothermal Project Leads to Second Thoughts After the Earth Rumbles*, Sept. 10, 2009, http://www.nytimes.com, last accessed: June 13, 2016.

[3] Künzle, Patrick: *Basler Geothermie-Projekt sorgt immer noch für Nachbeben (Eng. Geothermal project in Basel still causes aftershocks)*, July 08, 2013, www.srf.ch, last accessed: June 07, 2016.

[4] Smith, Ray: *Geothermal Energy Stuck in a Hole in Switzerland*, Aug. 05, 2013, http://www.ipsnews.net, last accessed: June 13, 2016.

[5] Rothfels, Jasper: *Erdwärme in Landau: Seit einem Jahr herrscht Stillstand (Eng. Geothermal heat in Landau: Since one year there is stagnation)*, March 25, 2015, www.rnz.de, last accessed: June 07, 2016.

[6] Geothermie Nachrichten: *Studie zum Potential der Geothermie in Europa bis 2030 (Eng. Study on potential of geothermal energy in Europe till 2030)*, Sept. 22, 2010, www.geothermie-nachrichten.de, last accessed: June 07, 2016.

[7] Holbein, B. et al: *System Platform Approach for the Effective Development of Borehole Tools Solving General Problems*, *proceedings*, 3rd European Geothermal Workshop, Karlsruhe, Germany, October 15-16, 2014.

[8] Spatafora, L. et al: *The GeoKam – A Tool for Video Inspection in Hot Deep Geothermal Boreholes*, proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22-24, 2016.