3D Modelling of Hexapod Manipulators in Drilling Rigs

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Kurzfassung
Im Rahmen eines Projektes zur Entwicklung eines neuartigen Geothermie-Bohrverfahrens wurde ein Schweißroboter entworfen, mit dem die bis zu 12 m langen Rohrstücke positioniert und mit einer Kraft von über 2000 kN miteinander verpresst werden können.
Um das Risiko bei der Entwicklung eines Schweißroboters auf Basis eines Hexapod-Manipulators zu minimieren, wurden mehrere Projektphasen durch umfassende Simulationen begleitet. Dadurch konnte das Grundkonzept frühzeitig validiert werden, ohne zusätzlichen Hardware-Aufwand in Kauf nehmen zu müssen.
Während der Entwicklung und des Baus des Prototypen konnte sowohl die Regleroptimierung bereits mit vielen realen Störeinflüssen als auch die Software-Entwicklung für die Steuerung durchgeführt werden. Diese Vorgehensweise kann die Entwicklungszeit erheblich reduzieren und ermöglicht durch einen höheren Reifegrad des Prototypen in seiner anschließenden Erprobung eine frühzeitige Konzentration auf die Prozessoptimierung und die Industrialisierung dieses neuen Geothermie-Bohrverfahrens.

Abstract
A welding robot was designed as part of a project for the development of a novel geothermal drilling process, to position the tubes reaching a length of up to 12m and bond them with a force of more than 2,000kN.
To minimise the development risk for the welding robot based on a hexapod manipulator, several project phases were supported with extensive simulations. This enabled us to validate the basic concept early on without incurring additional expenses for hardware.
During the design and construction of the prototype we were able to optimise the controls using a wide range of real-life disturbance effects and develop the control software. This approach presents an opportunity to considerably shorten development times and create a more mature prototype, which in turn allows
concentrating on process optimisation and industrialisation of this new geothermal drilling process early on.

**Introduction**

Earth drilling for geothermal sources is characterised by the use of borehole casing which is to enhance the persistence of a borehole several kilometres deep. After drilling, a casing made of special steel is positioned inside of borehole and widened to allow a continuous support at maximal inner diameter. The construction of a tubular string from individual tubes that have been screwed together carries a high risk of leakage and loss of stability during production and is relatively expensive.

The development of a novel geothermal drilling process\(^1\) is aimed with the goal of reducing the costs of the wellbore construction about 30% and the entire lifecycle cost about 50%.

A fusion press welding process development is going to deliver tighter, ridgid and reliable tubular connections.

A welding robot was designed as part of this development project to position the 12 m tubing (max. diameter: 300 mm, max. wall thickness: 25.4 mm) along the string at a distance of 5 mm from each other, to melt the ends of the tubes and bond them with a force of more than 2,000kN.

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\(^1\) Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Project No. 0325073, „Konzept, Entwicklung, Fertigung, und Test eines innovativen und kostengünstigen Geothermie-Verrohrungssystems“

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![Figure 1: Principle of welding robot](image-url)
around the welding joint, assessing the spatial deviation of the two ends, see Fehler! Verweisquelle konnte nicht gefunden werden. This deviation is used to calculate the corrective vector which the welding robot takes into consideration during the welding process.

To meet the demanding requirements of the welding process, the welding robot needs to be extremely dynamic and accurate, including as far as drives and controls are concerned. These strict requirements and the high costs that arise mainly due to the strong forces required and the wide measurements of the welding robot lead to a very high development risk.

To minimize this risk, the entire development process is supported by SimulationX®:

- **Design phase:**
  Comparison of different technical solutions and proof of general suitability of the design without the need for a costly prototype

- **Development phase:**
  Examination of robust control concepts and various sensor types as well as the identification of realistic closed-loop gains running simultaneously with the development and construction of the prototype;
  a real-time model of the welding robot allows the simultaneous development of mature and robust control software

- **Test phase:**
  Concentration on process optimisation and preparation of industrialisation thanks to advanced prototype maturity (drives, controls)

We will now describe the design of the simulation model and selected simulation results.

**Simulation Model**

The concept of the welding robot is based on an electro-hydraulic hexapod with 6 hydraulic cylinders. Each of the six hydraulic cylinders has been fastened to the frame and the manipulator platform using special radial plain bearings, see Figure 2: .
The lower section of the tubing has been tightly connected with the manipulator platform using a clamp. The process model for the molten material is located at the lower end of the tube, and has been implemented with a 3D mass damper loose element, see Figure 3: . The parametrisation was carried out using force-displacement measurements of the welding process.

The fast motion dynamics during the welding process very much excites the free-swinging tube, and corresponding dynamic feedback to the manipulator platform and the clamp is to be expected. To better assess the effects of these dynamic
disturbances on the accuracy of the manipulator movement, the tube in the simulation model was simulated as an elastic bar using a 3D bar element. The control concept consists of a classic position control method for parallel kinematics, i.e. the setpoints are defined by a vector of platform coordinates, which in turn are transformed into a setpoint vector for each of the 6 individual axes via inverse kinematics. On the other side, force control overlaps the position control and supplies corrected values in accordance with the desired direction of force for the set values for the platform position. The actual force vector in relation to the platform is calculated by multiplying the cylinder forces (based on the cylinder pressure values) with the inverse Jacobian matrix.

Simulation Results

The difficulty of simulation and the subsequent optimisation of drive systems and control loops often consists in the realistic consideration of disturbance effects. Disturbances, in particular coming from sensor signals, time and again lead to much lower loop gains than originally simulated due to necessary filtering in real machines. Particularly when the dynamic requirements on the drive and control systems are high, this creates a considerable development risk, because during the design phase in particular, there is no information about real (or measured) disturbance effects. This means having to fall back on a profound host of experience, which Hydrive Engineering GmbH has been able to accumulate by commissioning a wide range of different machines and facilities. Such disturbance effects may include, in particular:

- Signal noise (quantitative assessment)
- Friction within components (stiction, fluid friction)
- Hysteresis within components, e.g. valve magnets
- Cycle times for control systems for input, filtering and output
- Delay times of sensors
The simulation results shown in Figure 4: exemplify the behaviour of the hexapod manipulator with a non-linear prescribed displacement at $t = 50$ ms and $t = 400$ ms, with an incremental displacement of force at $t = 200$ ms and $t = 300$ ms. In the range of $t = 50..400$ ms, the manipulator platform should hold the preset position as accurately as possible, even under a displacement of force at $t = 200..300$ ms.

The diagram below clearly shows that suitable measures (dark line) may ensure the positioning accuracy in the real-life machine within the prescribed range of $\pm0.1$ mm even when taking into account all real-life disturbance effects, while closing the 5mm welding joint within the prescribed time of 50 ms is also possible.
However, there are areas within the simulation model which cannot be reliably parameterised without taking measurements of the prototype. These include the consideration of flexibility of the tubing, because while its bending mode can be easily simulated with ideal clamping, there is no reliable data on the rigidity and damping of real clamping in the machine.

**Summary and Outlook**

To minimise the development risk for the welding robot based on a hexapod manipulator, several project phases were supported with extensive simulations. This enabled the early correction and validation of the basic concept (layout, dimensioning, etc.) without incurring additional hardware costs. During the design and construction of the prototype we were able to optimise the controls using a wide range of real-life disturbance effects and develop the control software. This approach presents an opportunity to considerably shorten development times and create a more mature prototype, which in turn allows concentrating on process optimisation and industrialisation of this new geothermal drilling process early on.
