# Automatic Positioning and Alignment for Hole Navigation in Surface Drilling

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## Abstract

**Satellite-based positioning is becoming the prevalent solution for positioning and alignment of drill holes in open pit mines, quarries and construction sites. This is due to the accuracy and convenience of the systems, leading to improved blasting quality and thereby reduced costs and improved productivity. In a conventional hole navigation system, the operator is assisted by precision sensors and a satellite positioning receiver which compare the boom position and attitude to those pre-defined by a drilling plan. While such an approach provides a superior accuracy of the holes in comparison to conventional systems, the boom still has to be positioned manually using the rig controls. This work describes an automatic hole positioning and alignment system developed for drill rigs. The novelty of the solution is in the surface drilling application and the versatility of a typical drill boom. The system has been tested both in a simulated and a prototype environment. The main result is that automatic positioning improves the positioning accuracy and reduces the time required for the positioning task. This is because the automatic system overcomes the main restrictions of manual operation, namely the time and attention needed to position the boom given its dynamics and the actuator-based controls. Furthermore, the operation of the automatic positioning system is effortless and fast. These developments lead to further improvements in drilling quality, which in turn yields better blasting results and higher productivity in excavation. The developed system is also an essential part of remote operated or autonomous drill rigs.**

### Keywords

**Automation and control, drill rig, hole navigation, surface drilling, positioning, alignment, autonomous drilling, drill automation**

## 1 Introduction

Drill and blast -method is the dominant practice of excavation for moderately to very hard rocks with a low fracture density [1]. This is due to the speed of the method and its cost/yield ratio per excavated volume, i.e. excavation productivity.

Figure 1. A modern surface drill rig.

According to its name, the method involves drilling holes into rock for charging of explosives and consequently detonating the explosives to fracture and move the rock mass. In open pit mines, quarries and construction sites, the holes are drilled using surface drill rigs, see Figure 1 for an example.

To achieve the desired results in blasting, the drill holes need to be positioned and aligned accurately using the boom of the drill rig. This lies at the responsibility of the operator controlling the drill rig.

Utilization of Global Navigation Satellite System (GNSS) positioning has become the prevalent technical solution to the placement of holes. In such a setup, the rig operator is assisted by a system comprising a satellite positioning receiver and precision sensors for the boom. The system measures and compares the boom's position and attitude to those pre-defined by a drilling plan stored into the system.

While such an approach provides a superior accuracy of the holes in comparison to conventional systems, the boom of the rig still needs to be positioned manually using the rig controls. Typically the boom movements are controlled by a number of 1- or 2- axis levers, joysticks or buttons. The controls may be hydraulic or electric.

The drill rig boom is a complex structure in terms of mechanics and kinematics. It may, for example, consist of six two-directional actuators. Therefore, positioning and alignment of the boom includes 12 distinct movements. Regardless of the actual controller configuration, positioning and alignment is a challenging three-dimensional task, especially for inexperienced operators [2].

This paper describes a more user-friendly solution to control the boom automatically using the control system of the drill rig. The feature simplifies the operator's tasks and provides a faster and more accurate positioning of holes in comparison to manual operation.

Automatic positioning makes it possible to operate one or more drill rigs more conveniently from a remote control station. The automatic mode is also an enabler technology for autonomous drill rigs. Remote operation and autonomy minimize the need for human intervention and presence at the work site. This provides solutions to the present issues of safety, labor cost and limited availability of skilled workforce.

From the dimensioning standpoint the main load for the boom system consist from the drill, the feed system and other components, including the drilling tools. Typical boom masses are in the range of three to ten metric tons. The boom structure is relatively elastic compared to the mass it carries, which has to be taken into account in designing the control algorithms.

The paper is organized as follows. Section 2 explains the positioning and alignment task in more detail and its significance to excavation results. Section 3 describes the principles of satellite positioning systems currently in use, followed by a description of the conventional manual positioning mode in Section 4 The developed automatic
positioning and alignment solution is described in Section 5, and its performance and benefits are described in Section 6. Some notes on system development are given in Section 7. The paper is summarized in Section 8.

# 2 Positioning and Alignment in Drilling

## 2.1 Positioning and alignment

A drill hole is determined by its starting point on the rock surface, alignment, and depth, as defined in a drilling plan. Prior to actual drilling, the drilling boom must be correctly placed to achieve desired position and alignment of the hole, see Figure 2.

Positioning of a drill hole has to be done with a centimeter level accuracy. A typical requirement is that deviation from the planned location should not exceed the hole diameter.

Positioning is the process of moving the bottom of the drill feed boom, namely the drill bit, to coincide with the above-ground extension of the hole line. That is, the drill bit is positioned such that when pushed against the

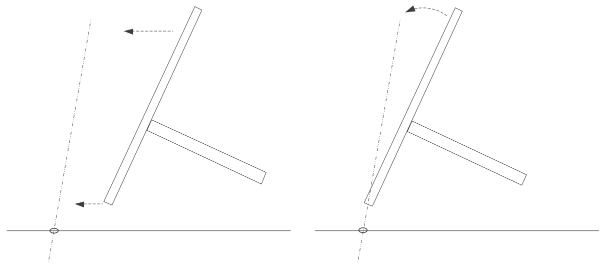

Figure 2. Positioning (left) and alignment (right) of drill boom.

ground, the bit lies at the desired starting point of the hole. Positioning is typically conducted with a sufficient margin between the lower end of the feed boom and ground surface, in order to avoid the boom from colliding into ground while being moved. Ground may be uneven and there may also be rocks and other obstacles in the area of movement.

Alignment is the process of turning the feed boom, parallel to the hole line. This is conducted in order to drill the hole in the direction defined in the drilling plan.

Note that positioning and alignment are, in principle, independent of each other. In practice, however, changing the alignment of the boom typically affects the drill bit location, and vice versa, due to the mechanics of the boom structure.

Depending on the situation and the operator's work practices, the order of positioning and alignment tasks may vary and they may also happen simultaneously.

## 2.2 Typical errors

Figure 3 provides examples of typical errors in drilling related to positioning and alignment. Incorrect positioning (Figure 3.a) yields a hole that is otherwise correct but at an incorrect location.

Incorrect alignment (Figure 3.b) yields a hole that starts at the right location, but the rest of the hole cylinder

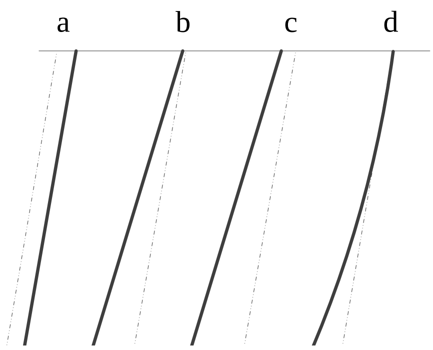


Figure 3. Examples of typical drilling errors: a) incorrect position, b) incorrect alignment, c) incorrect position and alignment, and d) hole deviation.

and ultimately the bottom of the hole are at incorrect locations. Note that an extensive error in alignment will result in the hole bottom to lie at an incorrect depth, too. If both the position and alignment are erroneous (Figure 3.c), the above effects are even more severe.

Hole deviation (Figure 3.d) is not directly attributed to incorrect positioning and alignment. In rock conditions where deviation is likely to occur, an incorrect alignment may trigger or increase the deviation, especially if the desired alignment has been specifically planned to minimize the deviation. Hole deviation may also add to the errors caused by incorrect position or alignment.

### 2.3 Contribution to excavation results

A high accuracy of drilling is crucial for controlled, safe blasting of the rock, which directly affects the costs of rock excavation and thus the productivity.

Positioning and alignment errors in the first row may result into reduced burden (distance between the first row of holes and the free edge of bench), increasing the risk of flyrock and consequent hazards during blasting.

Positioning and alignment errors affect also the distribution of explosives in the rock, and thus the specific charging changes. This results into suboptimal fragmentation of rock producing unevenly sized rock containing oversized boulders and/or an excess fraction of fines. In addition, the floor of the rock may become uneven. These factors complicate and add cost to loading and crushing operations. Furthermore, additional breaking or blasting of boulders may be required. The fragmentation of rock also affects the end product quality and yield in aggregate quarries and is thus a major economical factor.

There are also secondary effects from drilling accuracy and blasting results. An uneven or highly fractured rock floor is more difficult to operate on afterwards and may require filling to make the ground surface even. Drilling holes through fractured or filled rock floor contains a risk for holes to collapse or get blocked quickly after drilling has been completed. Controlled blasting assists also in conserving slope stability and thus in making the operation of the quarry safer and easier.

In [3], it has been estimated, based on three case studies, that the cost savings in drilling and blasting only attributed to satellite positioning are 25%. The savings arise, e.g., from productivity, reduced idle times, improved mine planning, and improved fragmentation.

## 3 Satellite-based navigation in drills

GNSS-based hole navigation systems have become an industry standard for accurate positioning of holes. See [4] for a system example. In such systems, the required accuracy is attained with real-time kinematic (RTK) positioning. This approach uses two satellite antennas: one for the position information and the second for obtaining the compass direction of the drill rig frame.

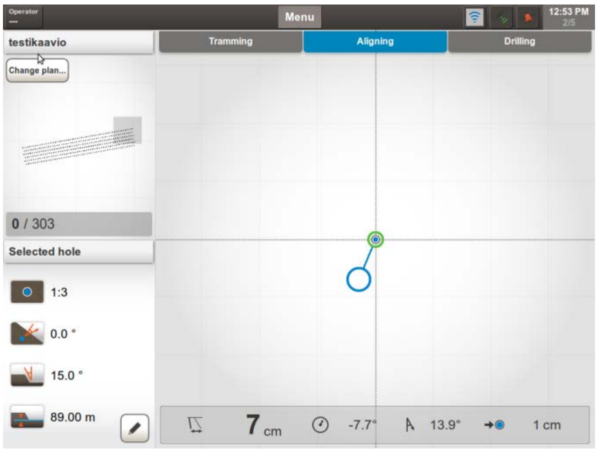


Figure 4. Graphical user interface of a GNSS hole navigation system [4].

In addition to the GNSS instrumentation, the drill rig is equipped with precision sensors for measuring the orientations of all boom joints. These are needed to calculate the drill bit position and feed boom alignment in the selected coordinate system.

The desired hole locations are provided by a drill plan that is downloaded into the navigation system. The plan is a file containing the locations and inclinations of the holes in a format understood by the system. Typically the plan is formatted according to the IREDES standard [12]. By combining the data from the positioning and kinematics calculation and comparing this to the information attained from the drill plan, the system guides the operator while steering the drill feed boom into the correct position and inclination. See Figure 4 for an example GUI.

In practice there is always some difference between the planned and realized hole locations. These differences are documented by storing the actual hole positions and inclinations into the navigation system. This data can be used, for instance, to review the planned charging of explosives, to monitor the quality of drilling or to optimize the overall drill and blast process.

In many worksites the documentation and review of hole locations data prior to blasting is mandatory. The data can be further supplemented by storing and combining measurement while drilling (MWD) data into the analysis.

The GNSS hole navigation system can also be utilized without a drilling plan. In these cases the hole locations are determined by the operator or have been marked on the ground. The system then documents the realized hole locations for further reference.

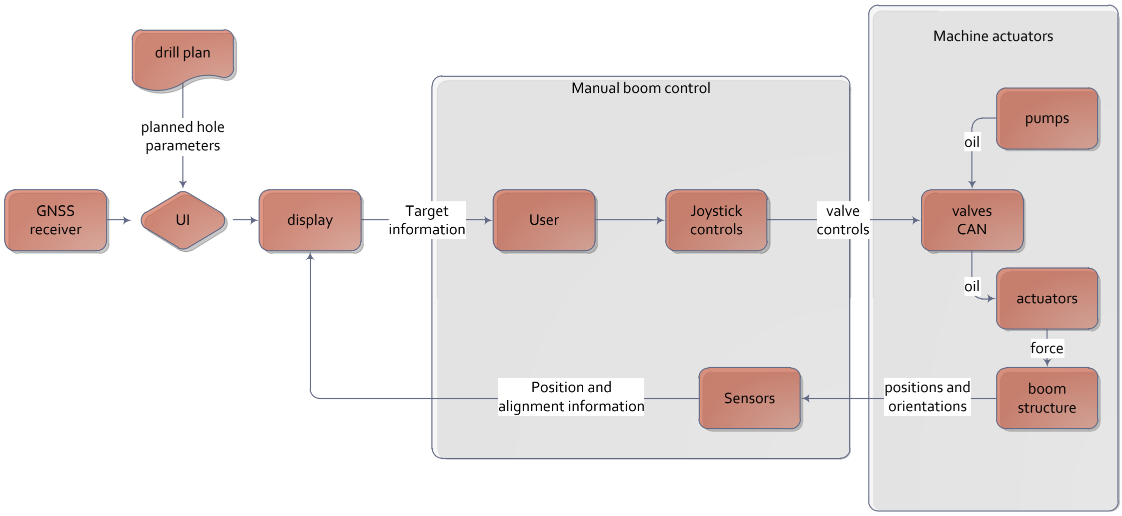


Figure 5. Block diagram of the manual positioning system

## 4 Manual positioning and alignment

The conventional method of hole positioning and alignment is manual direct hydraulic control of the boom that is assisted by the GNSS hole navigation instrumentation as described in Section 4. The feed boom positioning and alignment work phase begins after the operator has driven the drill rig into a location from which it is possible to reach the hole to be drilled. Here, “to reach” means that the feed boom can be aligned and positioned to correspond the drill plan.

The operator uses the controls provided by the drill rig to adjust the boom position and inclination. A typical drill rig boom has six degrees of freedom (six two-directional joints). A distinct control, e.g., a lever or a button, is required for each of the joints. As 12 distinct movements are needed, a (2x3), (3x4), or (6x2) control configuration is necessary.

From the user control commands, the control system of the drill rig forms control signals to the hydraulic valves regulating the oil flow to the boom actuators, which are typically hydraulic cylinders. In the direct control mode, each valve and actuator is controlled individually.

The resulting movement is measured by the boom sensors. The position and attitude of the boom are computed with forward kinematics based on the sensory data and provided to the operator via the system display.

There are downsides in the manual direct control of boom actuators. Firstly, regardless of the control configuration, positioning the boom manually is a complex three-dimensional task requiring considerable attention from the operator.

Secondly, movement of one actuator and joint has an effect on the overall boom position or attitude and therefore the target angles for the other joints are affected. For example, a change in the boom turn angle may change the feed boom alignment and drill bit position. If a joint or actuator is moved, further corrective movements in other joints may be needed. Therefore, it is not possible to reach the desired position and alignment by just controlling each of the joints respectively.

For these reasons, manual positioning and alignment is a time consuming task, especially for inexperienced operators. While the GNSS system greatly assists in the task, the resulting hole navigation speed accuracy depend ultimately on the operator’s skill and experience. These drawbacks can be overcome with an automatic positioning system.

## 5 Automatic positioning system

The GNSS-based hole navigation system described in Sections 3 and 4 enables to automate the positioning and alignment process. In the automatic mode, the control system calculates the desired joint angles for the boom structure and controls the valves and actuators jointly so that the desired joint angles are met. With an automated control, the operator’s task is greatly simplified as the automation can be activated, for example, by using a hold-to-run -type switch. With such a control mode the operator just supervises the actions and interferes only when necessary.

Block diagram of the automatic positioning system is given in Figure 6. Target values for the feed boom position and alignment are obtained from the drill plan. Combining the targets and forward kinematics data on the current boom position, the target joint angles can be computed using inverse kinematics (IK) [5]. Once the

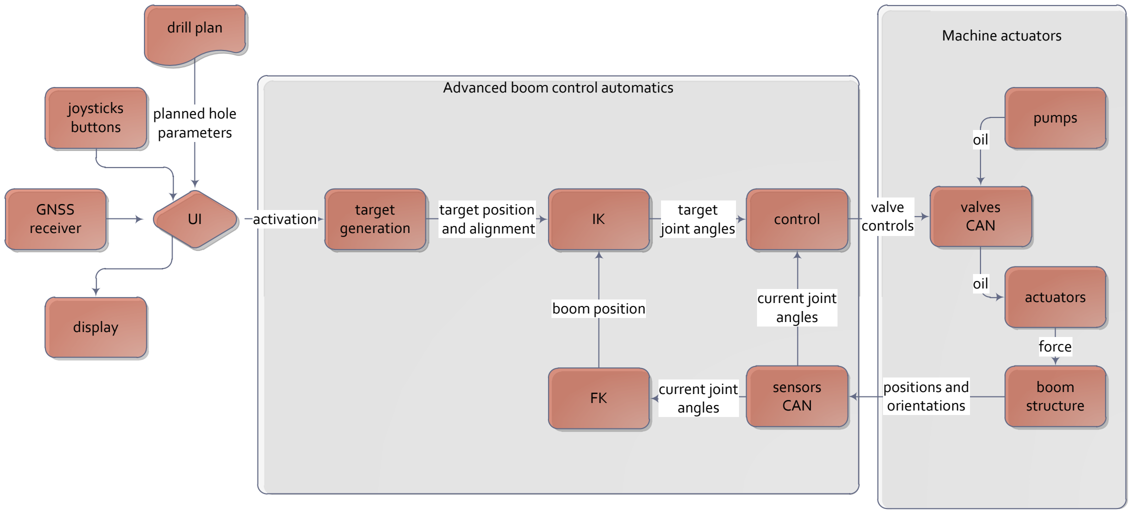


Figure 6. Block diagram of the automatic positioning system.

current and target values for joint angles are known, automatic positioning and alignment can be done by using controllers to regulate each of the valves.

The challenges to control the boom can be divided into three categories. First, the boom kinematics has to be controlled in a reasonable way. The second challenge is to measure the boom angles accurately and fast enough in a hostile environment. The third challenge is to maintain the stability and the performance of the nonlinear feedback loop including hysteresis, state dependent inertias and a fast IK solver.

Drill rigs operate in hostile environments where heavy vibrations, reactive chemicals, dust and other sharp hard particles may be present. This requires the instrumentation to be as minimal as possible for reliability reasons. In addition to reliability, a minimal instrumentation is important for keeping the purchase price of the rig as low as possible. Thus, the solution cannot be based on improving the instrumentation.

The kinematics and the feedback control have a tight link together. Inverse kinematics is a part of the control loop and a major factor in the observed response of the system. Consequently, the inverse kinematics and the feedback control problems cannot be solved separately.

The IK problem is nonlinear and typically leads to an iterative solution. The solution of the joint angle problem is typically ambiguous. However, inside a control loop the solution should be made unambiguous to avoid random discontinuations that cause severe control problems. Our approach to solution selection is to minimize an $l^2$-norm. One commonly used method is to use Tikhonov regularization [6]. See [11] for some typical solution methods for IK problems.

In our case coordinate system is fixed to the operator's position in cabin. The hole coordinates are given in the global coordinate system. These two coordinate systems have to be kept constantly synchronized during the positioning.

The boom control is a nonlinear control. A Bayesian probability [7] based linear-quadratic-Gaussian (LQG) control or a robust control method could have been used. However, in a nonlinear case the error distribution is state dependent. There is relationship between the nominal performance, the robust performance and the robust stability [8]. However, the characterization of the modeling errors is not easy and robust methods tend to result in control laws that do not fulfill the requirements for accuracy and speed.

To achieve the requirements, while lacking a formal approach, a heuristic ad hoc control law was utilized. The control law is basically a simple proportional control with gain scheduling [10] with a few heuristic modifications. The control law was designed from the stability standpoint in a similar framework as in [9]. The Lyapunov function properties guided to avoid the measurement delays, or more generally, the slow responses in the open loop.

In different operation modes the priorities are different. Stability has to be maintained in fast movements, and accuracy is achieved with smooth and slow movements. A slow movement generates smooth excitations and gain scheduling can be used to improve accuracy in special conditions.

The use of heuristics was attempted to keep as little as possible with maximum simplicity, because excessive use of heuristics makes it difficult to generalize the system. The main factor guiding the development was to make sure that the system is robustly stable at all stages, including mode changes.

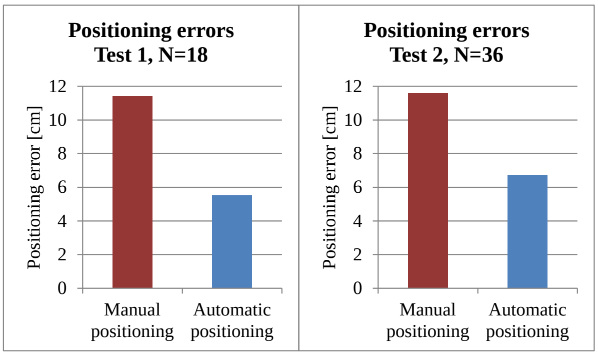


Figure 7. Positioning errors for manual and automatic modes in the two test cases.

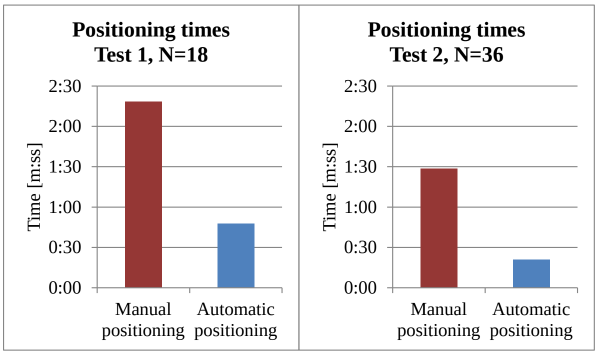


Figure 8. Positioning times for manual and automatic modes in the two test cases.

## 6 System benefits and performance

The automatic positioning feature has to be faster and more accurate in comparison to the manual positioning mode. The operation has to responsive with reasonable trajectories. Given the mass of the boom and the forces involved, the movements have to be initiated and stopped smoothly to avoid unnecessary loads on structures.

The accuracy and speed of positioning was measured using operators as test subjects in a drill rig simulator. Simulated environment was selected to allow repeatability of experiments and accurate measurement of preci-sion and positioning times.

The tests were conducted in two separate sessions. In the first session, a version of the algorithms was tested. In the test, six operators were asked to perform a pre-defined positioning task on three respective holes, resulting into N=18 test cases for both systems. In the second test session, a modified version of the algorithms was test-ed, now with six holes for each of the operators (N=36).

The averages of measured positioning errors are given in Figure X and positioning times in Figure Y. For both test cases it is clear that the automatic mode is faster and more accurate in comparison to the manual mode. The error of the manual mode is about 11.5 cm in both cases and is reduced to 5.5 cm in the first case and 6.7 cm in the second case. The average positioning time is reduced in the first case by 64% from 2:19 [m:ss] to 48 seconds, and by 76 % in the second case from 1:29 (m:ss) to 21 seconds. The variations in the positioning times in the two test cases are explained by the differences in the positioning setup.

The time required for manual positioning is explained by the precision of the instrumentation. The use of a GNSS hole navigation provides a good accuracy, especially in comparison to traditional systems where hole positions were determined visually without any instrumentation. However, it takes time to position the boom manually within the precision provided by the GNSS system. The automatic system does not have this limita-tion, and is able to achieve an even higher accuracy. In addition to these quantifiable results, the automatic mode is more pleasant to use for the operator, see [2] for more details on usability.

## 7 Development notes

The drill rig control system is a complex distributed system. Development and integration of a new feature into a distributed control system is challenging with regard to development time and performance verification. The algorithms developed herein were complicated, making these challenges even harder.

Had the new functionality been developed directly into the control system, the time required for each change-test iteration would have been long. This would have increased the total development time and cost unnecessarily. These issues were tackled with a rapid control prototyping (RCP) system developed in collaboration with a third party.

The RCP system uses an external computer connected to the drill rig control system. The computer communi-cates with the control system, reads the necessary inputs for the development-stage algorithms, computes the valve control commands and transmits them back into the control system. With the developed RCP system, the external algorithms could be run without interference or modifications to the actual drill rig control system or its

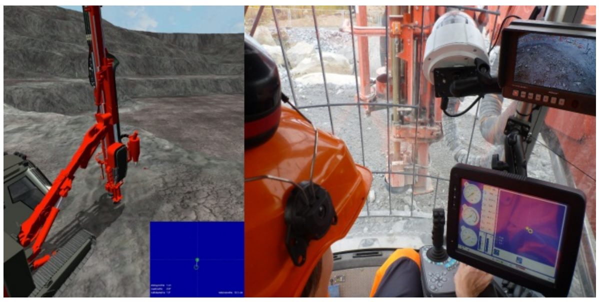

Figure 9. Illustration of the developed feature and UI in a simulator development environment (left) and on an actual rig (right).

software.

Early phases of development were done within a simulated environment (see Figure 9) to warrant safety and to avoid the practical constraints related to testing on an actual drill rig. Once the functionality of the algorithms was proven with the simulator, the setup was transferred onto an actual rig for testing and refinement. At both stages the observed modification needs could be almost instantaneously implemented and tested.

Once complete, the developed features were integrated into the control system using code generation. In this manner, there was no need to give further specifications or to re-program the algorithms for integration. This resulted into further savings in development time. Furthermore, there is no risk of introducing additional errors in programming as the as the algorithms are contained in the code generation results and no modifications are needed. The time savings were not formally measured but observed to be major, and in line with other cases where high-level programming languages and code generation is used [13].

## 8 Summary

This paper has introduced an automatic positioning and alignment system for surface drill rigs. The system is based on a conventional GNSS-based hole navigation system that has been supplemented with an automatic control mode comprising of target generation, inverse kinematics and control algorithms that have been integrated into the system.

The system was developed utilizing RCP methods that resulted in reduced development lead time. The main challenge in the development was to achieve a responsive yet stable control behavior, given the mechanical and dynamical properties of a drill rig boom. The system does not require additional sensors in comparison to the existing GNSS hole navigation system.

The developed automatic mode is more accurate and faster in comparison to manual positioning. It is also more pleasant for the operator to use. This provides an improved workflow and productivity, as well as an improved drilling quality with consequent benefits of production and cost to the overall excavation process. Authors believe that the developed system will become an industry standard in terms of safety, performance and automated equipment.

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