



(51) International Patent Classification:

G06Q 10/04 (2012.01) *G06Q 10/06* (2012.01)
E21B 44/00 (2006.01) *G06Q 50/02* (2012.01)
G05D 1/02 (2006.01)

(21) International Application Number:

PCT/SE2016/050924

(22) International Filing Date:

29 September 2016 (29.09.2016)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

1551257-7 1 October 2015 (01.10.2015) SE

(71) Applicant: **ATLAS COPCO ROCK DRILLS AB**
[SE/SE]; 701 91 Örebro (SE).(72) Inventors: **LUNDH, Robert**; Brickebergsvägen 64, 702 21 Örebro (SE). **JOYCE, Stephen**; Tingstorp 319, 718 94 Ervalla (SE). **MANSOURI, Masoumeh**; Nygatan 45A,

LGH 1201, 702 11 Örebro (SE). **PECORA, Federico**; Hertig Karls allé 15, 703 40 Örebro (SE). **ANDREAS-SON, Henrik**; Erikshultsvägen 1, 702 29 Örebro (SE).

(74) Agent: **EHRNER & DELMAR PATENTBYRÅ AB**;
P.O. Box 10316, 100 55 Stockholm (SE).

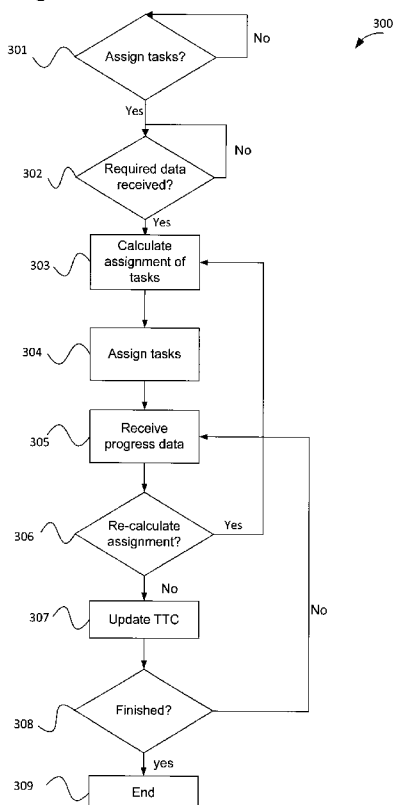
(81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH,

[Continued on next page]

(54) Title: METHOD AND SYSTEM FOR ASSIGNING TASKS TO DRILL RIGS

Fig. 3



(57) **Abstract:** The present invention relates to a method for assigning a set of tasks to a plurality of drill rigs (200A, 200B; 701-703), said tasks including drilling of holes by said plurality of drill rigs (200A, 200B; 701-703). The method includes: - defining a first set of constraints to be fulfilled when assigning tasks to said plurality of drill rigs (200A, 200B; 701-703); - finding an overall solution fulfilling said first set of constraints by solving each constraint as a sub-problem, a solution to at least one sub-problem being dependent on the solution of at least one other sub-problem; - said overall solution fulfilling said first set of constraints being determined when a solution to a first of said sub-problems is validated by solutions of others of said sub-problems, and - assigning tasks to said plurality of drill rigs (200A, 200B; 701-703) according to the determined validated overall solution, wherein tasks of said set of tasks are arranged to be carried out at least partially overlapping in time by said plurality of drill rigs (200A, 200B; 701-703).



GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT,
LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE,

SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA,
GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

METHOD AND SYSTEM FOR ASSIGNING TASKS TO DRILL RIGS**Field of the invention**

The present invention relates to operation of a drill rigs,
and in particular to a method for assigning tasks to drill
5 rigs according to the preamble of claim 1. The invention also
relates to a system and a drill rig.

Background of the invention

In mining and tunneling, for example, there is a constant
ongoing process of improving efficiency, productivity and
10 safety. Examples of changes/improvements that are carried out
to an increasing extent, perhaps in particular in mining, is
the automation, fully or partly, of various processes
occurring in mining.

It is, for example, often desirable that at least part of the
15 vehicles/machines that are used in mining/tunneling can be
driven fully autonomous, i.e. without an operator being
required to influence the control/operation. In fact, the
operation of autonomous vehicles/machines are more and more
becoming key components in mining. Methods for localization,
20 mapping, control and motion planning have enabled development
and deployment of autonomous machines. However, with regard to
mining and construction, there are important hindrances when
it comes to employing a plurality of autonomous vehicles
simultaneously.

Summary of the invention

25 It is an object of the present invention to provide a method
for assigning tasks to drill rigs. This object is achieved by
means of a method according to claim 1.

The present invention relates to a method for assigning a set of tasks to a plurality of drill rigs, said tasks including drilling of holes by said drill rigs. The method includes:

- 5 - defining a first set of constraints to be fulfilled when assigning tasks to said a plurality of drill rigs;
- finding an overall solution fulfilling said first set of constraints by solving each constraint as a sub-problem, the solution to at least one sub-problem being dependent on the solution of at least one other sub-problem;
- 10 - said overall solution fulfilling said first set of constraints being an overall solution where a first of said sub-problems is validated by solutions of others of said sub-problems, and
- 15 - assigning tasks to said a plurality of drill rigs according to the determined validated solution, wherein tasks of said set of tasks are arranged to be carried out at least partially overlapping in time by said plurality of drill rigs.

The present invention, consequently, provides a method for assigning tasks to a plurality of drill rigs. These machines
20 can be a manually operated drill rigs or autonomous drill rigs. When the drill rig is working autonomously, the assigned tasks can be dispatched, communicated, to the drill rig, which then carries out the tasks. It is also contemplated that the drill rig is a manually operated drill rig, in which case the
25 tasks can still be determined according to the invention and communicated to the drill rig, where the tasks can then be displayed to an operator when performing the tasks using the drill rig and guide the operator to maneuver the drill rig in a manner fulfilling the constraints.

Hence the assigning of tasks according to the invention is arranged to assign said tasks to a plurality of drill rigs, which can be autonomous drill rigs or manually operated drill rigs, or a combination thereof. Furthermore, the drill rigs
5 may be arranged to be autonomously driven between positions for performing tasks. Drilling of said holes are arranged to be carried out at least partially overlapping in time by a plurality of drill rigs. That is, drill rigs can be carrying out different tasks of said set of tasks concurrently.

10 With regard to mining and construction, there are important hindrances when it comes to employing a plurality of autonomous vehicles simultaneously. Fleet automation, i.e. the operation of a plurality of drill rigs simultaneously, often involves solving several, strongly correlated sub-problems
15 such as allocating tasks to vehicles, planning vehicle motions, and vehicle coordination. This makes solving the overall problem of assigning tasks difficult. The invention provides a solution to solving such problems. According to the present invention, it is provided a method where a solution to
20 a problem of assigning tasks to autonomously operating drill rigs is obtained, where the number of tasks, to be performed, e.g. holes to be drilled, can be large, e.g. in the order of 30 or more, and where the solution can accommodate one or multiple drill rigs and tasks can be performed at least
25 partially concurrently.

The assigning of said set of tasks can therefore be solved as a higher level constraint satisfaction problem, a solution to the problem of assigning said set of tasks being searched from solutions to said sub-problems, each of said sub-problems
30 being solved as a lower level constraint satisfaction problem

providing a solution to constraints of the higher level constraint satisfaction problem.

According to the provided solution, the problem of assigning tasks is stated as a set of tasks to be assigned to the drill rigs given a set of constraints with regard to the assigning and carrying out of the tasks. That is, a set of requirements that must be fulfilled when the tasks are carried out. These requirements, in turn, are arranged to form sub-problems, which are solved sub-problem by sub-problem, but where sub-problems depend on each other, so that a solution of one sub-problem will be dependent on the solution of another sub-problem. According to the invention, this is accounted for when searching an overall solution from the solutions of sub-problems by requiring a first sub-problem to be validated by solutions to other sub-problems.

The constraints can, for example consist of one or more of:

- drill rigs must not collide with obstacles/each other when moving from one drill target to another;
- Drill piles resulting from drilling constitute obstacles that must not be run over;
- the drill rig must be able to move away from the drilled holes and not be locked in by drill piles;
- Motions should be executable by the drill rigs i.e., motions should be kinematically feasible. The planned motions of the drill rig must be able to be carried out in reality;
- The solution must respect spatial constraints with regard to possible movement of the drill rigs, e.g. the drill rigs must stay within a defined geographical area, e.g. a geofenced area.

The solution to the assigning of said tasks is found by validating a solution to one of said sub-problems by solutions of the others of said sub-problems. That is, the solution to a sub-problem is considered a valid solution, if the solution
5 allows solutions also of the other sub-problems that fulfill the given constraints. Consequently, it is ensured that a sub-solution is such that it does not prevent other sub-problems from being solved.

If a solution to a first sub-problem is not validated by a
10 solutions to other sub-problems the solution to the first sub-problem is discarded and another solution to the first sub-problem be searched and be validated by solutions to other sub-problems. This can be iterated until a solution has been found that fulfills all sub-problems.

15 A common representation of the sub-problems can be used, where said tasks are represented by variables. In this way, solver algorithms of the sub-problems share a common search space when searching a solution to a sub-problem so that the solution to a sub-problem can be validated by solutions to
20 other sub-problems in an efficient manner.

The use of constraints substantially reduces allowable solutions, with the result that much less computational power is required to solve the overall problem of assigning tasks.

Consequently, according to the invention, the overall problem
25 is divided into a plurality of sub-problems and the mutually feasible solutions to the individual sub-problems are found, where solutions from different sub-problems are combined.

Furthermore, a heuristically guided backtracking search can be used to find a solution to the overall problem in the joint
30 search spaces of the sub-problems.

Priorities can be assigned to said sub-problems, so that a solution to the assigning of said tasks can be determined by validating a solution to a higher prioritized sub-problem by solutions to lower prioritized solutions. In this way, it can be ensured that sub-problems that depend on the existence of a solution of another sub-problem are solved after such solution exists.

When solving the assignment of tasks, a representation of the tasks to be carried out by means of said drill rigs can be used. For example, the representation may include positions at which the tasks are to be carried out, and also data regarding what the task consists of. A representation of said drill rigs can also be used when solving the assignment, where the representation of the drill rigs may include a representation of speed and capacity, e.g. in the form of drilling or loading.

As mentioned, the tasks can be arranged to be carried out within a border confining a geographical area, where the drill rigs are not allowed to cross the border.

According to one embodiment it is determined start times and end times for performing each of said tasks, the start times and end times of a task being defined in relation to start times and end times of the other of said tasks, and said assignment of said tasks including a start time and end time for performing said tasks. In this way, drill rigs can be scheduled to perform tasks such that they do not collide when operating in overlapping geographical areas.

Hence, a plurality of drill rigs can simultaneously perform different tasks of the set of tasks, where the drill rigs, when carrying out the tasks, may be present at a same location

but scheduled to be at the same location at different times so that they do not collide.

During operation, i.e. when actively performing said tasks, progress data regarding fulfillment of said tasks can be transmitted from said drill rigs, and start times and end times of the tasks can be recalculated on the basis of received progress data, so that it can be accounted for e.g. tasks taking shorter or longer periods of time to carry out than expected.

Furthermore, an estimated time of completion and/or time to completion of said set of tasks can be determined, and displaying said estimated time of completion and/or time to completion. In this way, other work, such as other kinds of tasks, to be carried out after the tasks have been completed, e.g. by means of other machines can be scheduled in a cost-effective manner.

The estimated time of completion and/or time to completion of said tasks can be updated on the basis of progress data received from said drill rigs when carrying out said tasks. In this way, a proper estimate can always be obtained, e.g. if the performance of the tasks takes longer than expected.

The problem of assigning tasks to said drill rigs can be arranged to be re-determined when work is ongoing e.g. if drill rigs communicate deviations requiring a re-assignment of said tasks. For example, a drill rig may suffer a break down, or tasks may take longer than expected to carry out so that tasks must be reassigned to other drill rigs. Occurrences of this kind can be accounted for by re-determining the assignment of tasks in view of the changed conditions, so that

the ongoing carrying out the tasks can be continued, however with changes in the assignment of tasks to drill rigs.

The assigning of said tasks can further include a constraint such that, when said drill rig has finished assigned tasks, a defined end position can be reached by a drill rig without violating allowed movements within the area in which said tasks are being carried out. In this way it can be ensured that the drill rig can be moved away from the work area, e.g. if blasting is to be performed, without destroying work performed by tasks that has been carried out.

The assignment of said tasks can be performed from a location remote from at least one of said drill rigs, e.g. from one of the drill rigs, or from a control center being separate from all of the drill rigs.

The method of finding a solution to the assigning of tasks to the plurality of drill rigs according to the invention can be arranged to be carried out by calculating/computing means, such as a computer or control unit e.g. in a control center or other remote location in relation to the drill rigs. According to embodiments of the invention, calculating/computing means are included in one or more of the drill rigs. For example, the method can be controlled by one drill rig instructing the one or more other drill rigs participating in the task at hand.

The invention also relates to a drill rig.

Brief description of the drawings

Fig. 1 shows a surface pit-mine drill plan and geofence restricting machine movements.

Fig. 2 shows a drill rig which can be utilized according to the invention.

Fig. 3 shows an exemplary method according to embodiments of the invention.

5 Fig. 4A shows an example of decisions in a sequencing of tasks sub-problem according to embodiments of the invention.

Fig. 4B shows an example of approach angles for drilling for a subset of holes to be drilled.

10 Fig. 4C shows an exemplary motion pattern of a drill rig when moving from a drilled hole to a hole to be drilled.

Fig. 4D shows an exemplary motion pattern of a drill rig close to a geofence.

Fig. 5 shows a motion pattern of a drill rig close to a geofence also illustrating piles of already drilled holes.

15 Fig. 6 shows a suggested sequence pattern for use when sequencing tasks near geofences.

Fig. 7 shows an example of scheduling of work of three machines to avoid collisions.

Detailed description of a preferred embodiment

20 Embodiments of the invention will be exemplified with reference to a specific problem in a mining application. The invention is, however, applicable in various other mining applications as well. Also, as explained above, the invention is applicable also when only one machine is present, and when
25 the one or more machines are manually operated.

However according to the example discussed in the following, a fleet of, i.e. a plurality of, surface drill rigs are arranged to operate autonomously and concurrently within a shared area of the open-pit mine, called a bench. Rock/ore excavation in mines of this kind often involves drilling of a set of drill targets in the bench. That is, at each predetermined target (position) a blast hole is to be drilled. The blast holes are then filled with explosive material that is detonated after all targets have been drilled. After the explosion, the ore is taken away and processed for mineral extraction. An example of a bench 100 is shown in fig. 1, where a plurality of holes (drill targets), indicated by a large number of black dots 101, are to be drilled for subsequent blasting. The geographical area making up the bench 100 is outlined and defined by an outer boundary 102, which, as will be explained below, indicates a geographical area to which the machines are confined and must not traverse in order to avoid accidents and/or collisions with surrounding obstacles such as rock. The boundary 101 thus constitutes a geofence.

Each drill target 101 can be seen as a task to be carried out, where a machine (drill rig) autonomously carries out a set of sub-tasks when completing the task of drilling the hole. These sub-tasks may e.g. include auto-tramming (automatically navigating) to the target (drill position) from its current position, leveling the drill rig (deploying jacks for leveling the machine in position for drilling, e.g. horizontally), drilling, de-leveling (retracting the jacks so the machine is placed back on its tracks) and moving away from the drilled hole. Fig. 1 further shows two drill rigs 200A, 200B which are to be used to drill the bench 100, and a control center 106 in which e.g. calculation according to the invention can be arranged to be carried out.

Fig. 2 discloses an exemplary side view of a drill rig 200 which may be utilized in a solution according to embodiments of the invention for drilling holes of a bench according to fig. 1. The drill rig 200 is only exemplary, and there exist various kinds of drill rigs of various designs that can be used according to the invention. The drill rig 200 constitutes a surface drill rig being used to drill vertical or substantially vertical holes using a drill tool attached to a drilling machine via a drill string. The drilling machine is slidably arranged along a feed beam. These elements are conventional and not explicitly disclosed. Instead they are represented by a drill tower 201 and a schematically indicated drill string 203 indicating ongoing drilling. The general technology used when drilling using a machine according to fig. 2 is well known per se. Drill rigs may also comprise a dust guard 202 to reduce dust from unnecessary spreading to ambient air and surrounding ground during drilling.

Irrespective of whether a dust guard is used or not, the drilling of a hole produces piles of excess material, drill cuttings, around the hole, and due to the formation of drill cuttings around the hole during drilling, there may be restrictions regarding the manner in which the drill rig can move away from the drilled hole. If the drill pile is run-over by the drill rig, drill cuttings may clog the hole so that the hole must be drilled again. Also, when maneuvering from one drill location to another, drill piles must not be run-over. If the drill rig comprises a dust guard or similar means, this may impose further restrictions regarding possible directions of movement when moving away from a drilled hole.

The need to avoid drill piles, consequently, imposes constraints regarding possible movements of the drill rig, in

particular with regard to holes to be drilled near the geofence 101 which may not be drillable from all directions, since this may require the drill rig to move into forbidden areas in order to clear a pile of drill cuttings of a drilled hole.

The drill rig 200 further comprises crawlers or wheels 205 to allow the drill rig 200 to be moved from one position to another, such as from hole to hole to be drilled.

The drill rig 200 also comprises a control system comprising at least one control unit 206, which controls various of the functions of the drill rig 200 and in particular operation of the drill rig according to embodiments of the invention, where the control unit can be arranged to control crawlers, drilling machine etc. by suitable control of various actuators/motors/pumps 207, 208 etc. Drill rigs of the disclosed kind can comprise more than one control unit, where each control unit, respectively, can be arranged to be responsible for different functions of the machine. The control system of the drill rig 200 further comprises transceiver means 209 for receiving instructions regarding tasks to be performed and controls crawlers, beam, drilling machine etc. to carry out the received instructions, and to allow data to be transmitted from the drill rig e.g. to a control center, the data e.g. including current work data such as position, current progress when drilling a hole, completion of a task etc.

The present invention provides a solution that can be utilized to use a plurality of autonomous drill rigs for automatically and simultaneously performing e.g. drilling of holes according to a bench 100 according to fig. 1, where drill rigs may be

maneuvered within overlapping portions of the bench 100 while simultaneously being confined to stay within the geofence 102.

Such autonomous drilling gives rise to a number of problems to be solved. As drilling across the bench 100 progress, piles of drill cuttings will be accumulated at each location where a hole has already been drilled, and hence a drill rig need not only take the immediately drilled hole into consideration, but the drill rig must also avoid piles that have accumulated during previously drilled holes. The distance between holes may e.g. be in the order of 0.5-2 times the machine length, which, as drilling progress, may render maneuvering complicated to avoid piles from previously drilled holes while simultaneously staying within the geofence. Also, drilling must be performed such that the machine when the drilling of the holes of the bench 100 is finished, is not "locked in" by piles of already drilled holes, but is able to move away from the bench, or to a particular position within the bench, prior to blasting.

A bench may comprise a relatively large number of holes to be drilled, e.g. in the order of 30-2000. Since drilling of a single hole inherently takes some time use of a plurality (i.e. at least two) of concurrently operating drill rigs may considerably reduce overall time for completing drilling of the bench so that blasting can be performed at an earlier point in time. This imposes additional aspects that must be attended to when performing autonomous drilling using a plurality of machines. For example, it must be ensured that drilled holes by one machine do not prevent drilling of holes for the one or more other machines. Also, it must be ensured that drilling performed by one machine does not hinder drilling of holes for another machine. In addition it must be

ensured that the machines do not collide with each other, i.e. are not present at the same location at the same time.

The automation of the operation of the fleet of autonomous operating machines involves solving of a plurality of problems that are strongly correlated. This makes solving the overall problem difficult, since a large number of solutions exist for each problem, thereby rendering it difficult from a computational point of view to find a common solution that solves all problems in a manner that also fulfills the further criteria, constraints, that usually must be met to obtain a working solution. Obviously, there are a huge amount of theoretical possibilities that can be evaluated in order to find a solution that works, thereby requiring large amounts of computational power. For example, in addition to the large number of holes to be drilled, these may be drilled from various directions with respect to a reference direction, different holes can be drilled by different machines etc. This renders solving of the problem complex. As will be explained below, it is preferred if changes to a determined way of assigning drilling of the holes to the various machines can be carried out underway as drilling progress.

According to the present invention, constraint satisfaction problem (CSP) solution is utilized to facilitate problem solving. CSP is well known per se and therefore not described in detail. The invention utilizes a two level CSP methodology that results in an efficient way of solving problems involving assignment of tasks to a plurality of autonomously operating machines that operate in overlapping portions of a geographical area.

The Drill Pattern Planning Problem of drilling the bench 100 of fig. 1 (denoted DP3 in the following) consists of computing

a drill plan that involves machines (drill rigs) reaching each drill target in the bench 100 and performing the necessary operations to drill the blast holes. The problem of assigning the drilling of the holes to a plurality of machines may be
5 subject to the following requirements:

- Machines should not collide with obstacles/each other when moving from one target to another;

- Drill piles resulting from drilling constitute obstacles that must not be run over by dust guard or other machines;

- Once drilling has been performed, the machine is limited in choice of movement when moving away from the drilled hole. According to the present example, the machine can only drive away from the target by backing after raising the forward dust guard 202a since this is the only part of the dust guard that
10 can be actuated according to the present example);

- Motions should be executable by the machines i.e., motions should be kinematically feasible. Hence, the planned motions of the machine must be able to be carried out in reality;

- It should be possible to modify the resulting solution once
20 drilling has started to account for events that occur once drilling has commenced;

- The plan should respect spatial constraints with regard to possible movement of the machines. For example, a geofence according to the above must oftentimes be defined and within
25 which the vehicles must operate to avoid collisions with e.g. surrounding rock or other obstacles or driving over edges.

An exemplary method 300 according to the invention is disclosed in fig. 3. The method can be arranged to be carried

out by calculating/computing means, such as a computer or control unit e.g. in a control center 106 or other remote location in relation to the drill rigs being utilized for drilling the bench. According to embodiments of the invention, means, such as calculating/computing means, are included in one or more of the drilling rigs 200A, 200B. For example, the method can be controlled by one drilling rig instructing the one or more other drilling rigs participating in the task at hand.

The method of fig. 3 starts in step 301, where it is determined whether a drill plan problem consisting of assigning tasks to autonomously operating machines, in this example drill rigs 200A, 200B is to be carried out. When this is the case the method continues to step 302. In step 302 it is determined if required data to assign the tasks have been received. For example, with regard to the present embodiment, this data comprises the locations of the drill targets, i.e. the positions of the holes 101 to be drilled, and the geofence 102 defining the bench 100. The drill targets and geofence are oftentimes based e.g. on a geological survey of the area and on the current production plans of the mine. This data is input into the system prior to solving the drill plan problem DP3. Also other restrictions and heuristics may be input.

The set of machines to be used for accomplishing the task of drilling the holes, in the present example drill rigs 200A, 200B, are also determined beforehand, and in general selected on the basis of the problem at hand, where the size of a fleet of drill rigs to be used can be based e.g. on the size of the bench to be drilled. Also, different kind of machines may be required if holes of different diameters are to be drilled according to the drill plan. The number of and/or types of

machines being available for the task at hand are input to the system. Further input may include initial positions of all machines, i.e. their current location or user defined starting positions, as well as desired final "parking" positions of the machines, e.g. in terms of an allowed area or position at which a machine is to be located once the drilling of the bench is completed.

When it is determined that required data has been received the assignment of tasks when drilling the drill plan is calculated in step 303, including time to completion estimation, according to the below. Steps 300-303 can be performed offline to compare different scenarios, e.g., different number of machines. In step 304 tasks are dispatched, i.e. communicated to machines. In step 305 progress data is received regarding the completion of the tasks, and in 306 it is determined whether a recalculation of the solution is to be performed. If so the method returns to step 303 for recalculation. In step 307 the time to completion of all tasks is updated, e.g. based on tasks taking longer than expected etc. as explained above and below. Also, time windows for performing tasks can be updated on the basis of actual progress of performing the tasks. In step 308 it is determined if the tasks have been carried out, and if so, the method is ended in step 309. If not, the method returns to step 305.

The calculation in step 303 is carried out according to the following. The requirements set out above regarding the drill plan problem DP3 pose several problems e.g., task allocation (of machines to target poses), motion planning, and coordination. These problems cannot be treated separately and independent from each other, since the solutions of each problem depend on each other. For instance, coordination must

lead to a sequence of target poses that accounts for the piles generated after drilling (which become obstacles that must be taken into account in motion planning).

Hence, it is necessary to subject the possible choices made to solve one problem to the choices made in resolving the other problems, e.g., verifying through motion planning that a chosen sequence of targets to drill will be kinematically feasible in reality. Because of these interdependencies, the drill plan problem is a hybrid reasoning problem. According to the invention, an approach is utilized in which the overall problem (e.g. drilling the holes of fig. 1) is divided into sub-problems, and the solution to the overall problem is searched for in the joint search space of these sub-problems.

The drill plan problem according to the present example can be divided into five sub-problems.

- A sequencing sub-problem. This sub-problem consists of deciding a total ordering of targets i.e., sequencing every pair of targets so that it is determined in which order targets (holes) are to be drilled.

- A motion planning sub-problem. This sub-problem consists of deciding the pose, alignment, of the drilling machines at each target. That is, it is determined the alignment of the machine in relation to e.g. a reference direction for each hole to be drilled and also the space required and traversed when moving from one hole to another. The alignment should be such that the holes can be drilled without disturbing piles of already drilled holes, and also ensure that the machine can move away from the drilled hole. Constraints on the orientation of the machine in certain target poses may be given (e.g., due to the presence of the geofence or other geographical constraints

like cliffs and walls present within the area to be drilled. The decisions are subject to kinematic constraints, obstacles and geofence, and must account for piles resulting from drilling, as well as the dust guard mechanism.

- 5 - A machine allocation sub-problem. This problem consists of allocating machines to targets given the available machines and their positions. Machine allocation also accounts for the need to reach a given end parking position.
- 10 - A coordination sub-problem. This sub-problem consists of scheduling machines. Solutions to this sub-problem consider spatio temporal overlap between machines, i.e. machines may traverse a same geographical point at the same or different points in time. The sub-problem also consider overlap between machines and piles, i.e. it must be ensured that piles
15 generated by one machine are not run-over by other machines.
- A temporal sub-problem consists of deciding when machines should carry out motion, drilling, leveling and de-leveling operations, subject to temporal constraints arising from coordination, sequencing, maximum achievable speeds, etc.
- 20 According to present example, Constraint Satisfaction Problem (CSP) solving is used to obtain a solution to the posed drill plan problem. CSP is well known per se, and hence the actual realization of the solving of the sub-problems when criteria are set can be performed in a conventional manner. A solution
25 to the overall problem is obtained by reasoning upon these five different sub-problems jointly. Candidate solutions for a sub-problem are validated by dedicated solvers. Each solver focuses on a subset of aspects of the overall problem, e.g., a motion planner verifies kinematic feasibility and absence of
30 collisions, while a temporal solver verifies that coordination

choices are temporally feasible. Validated solutions for each sub-problem can be seen as constraints that account for particular aspects of the overall problem. They can be maintained in a common representation, which is sufficiently expressive to model the search space of all sub-problems jointly. The common representation can constitute a constraint network where variables represent tasks.

According to the present example, a task is represented by a tuple $M = (gp, sp, r, P, m, S, T, A)$, where

r represents the machine (drill rig) which should perform the set of activities

$A = \{\text{drilling, leveling, de-leveling}\}$ at, respectively, starting pose sp and goal pose gp .

P is the path that r traverses to reach gp from sp , and is computed based on a map m of the environment (bench and drill holes).

S is a set of polygons representing sweeps of the machine's footprint over P when moving from sp to gp , and

T is a set of time intervals representing when r will be in each polygon contained in S . The time intervals can e.g. be absolute time intervals, or time intervals with reference to a start time at which the drill rigs begin drilling the drill plan.

Henceforth, $M(\cdot)$ denotes an element of the task tuple.

Let $\mathbf{M}$ be the set of all tasks in the overall problem at hand (one for each drill target). A solution to the overall problem is such that a value is decided for all elements of a task,

for each task in $M \in \mathbf{M}$. Each element is decided by solving one or more sub-problems.

Consequently, a task M can be viewed as a variable in a Constraint Satisfaction Problem whose domain represents all possible combinations of values that can be given to each element of M . Accordingly, a sub-problem can be viewed as the problem of constraining the domains of tasks so the requirements stated above are met. Hence, the solvers that validate solutions to the sub-problems are seen as procedures that post constraints to the common constraint network. As will be explained, adopting the CSP metaphor allows employment of heuristic search strategies for solving the overall problem.

The sub-problems listed above will be discussed in the following.

Sequencing sub-problem

The sequencing sub-problem consists of finding a total order of the tasks to be performed. A decision variable of this sub-problem is a task $M_i \in \mathbf{M}$ that does not have a preceding task. A possible value that can be assigned to this decision variable is a precedence constraint M_j precedes M_i , asserting that task $M_j \in \mathbf{M}$ should occur before M_i . M_j is a task for which it has not been already decided that it precedes another task. A sequencing solver verifies that tasks are totally ordered. Fig. 4A shows an example of decisions in this sub-problem. Fig. 4A discloses a portion of the bench of fig. 1 near the geofence 102 where the machine has to perform a turn. As can be seen the order of drilling the holes closest to the geofence is changed from the pattern before (consecutive) and

after (also consecutive) the turn at the geofence. In particular, the order is 166 -> 137 -> 168 -> 167 -> 138 -> 139 etc. The actual track of machine movement when performing the drilling close to the geofence may be relatively complicated, as will be seen below, in relation to the drilling of holes along a straight line, where movement pattern is straight forward (e.g. along a straight line).

Motion planning sub-problem

The motion planning sub-problem consists of finding a goal pose gp for each task $M_i \in \mathbf{M}$. A gp is a tuple $\langle x, y, \theta \rangle$ in which x and y represent the (geographical) position of a drill target on the bench, and θ is the orientation of the machine in relation e.g. to a reference direction. The decision variables of the motion planning sub-problem are tasks M_i such that:

(1) $M_i(gp)$ does not have a defined orientation, i.e., θ is not assigned to an angle,

(2) there exists M_j precedes M_i in the common constraint network, and

(3) $M_j(gp)$ has been assigned an orientation.

The number of possible values that can be assigned to a decision variable can be any suitable number of angles, where a limited set of angles can be used e.g. improve computational efficiency. According to the present example, a set of eight angles $\{\theta_1, \dots, \theta_8\} \in [0, 2\pi]$ are used, which can be evenly distributed over a full rotation $[0, 2\pi]$. A particular choice of approach angle for a target is only feasible if the machine can drive

away from the previous target $M_j(gp)$ and navigate to the end pose of a task $M_i(gp)$ considering piles created by all the preceding tasks.

For example, Figure 4B shows a selection of one feasible approach angle for some of the tasks discussed with reference to fig. 4A and hence with respect to existing sequencing constraints. The approach angles are represented by arrows, and the machines drive away from the targets in the opposite direction of the arrows.

The eight possible assignments to the decision variable determine eight different possible end poses of the machine $\{M_i(gp_1), \dots, M_i(gp_8)\}$, which differ only in the orientation of the machine in the goal pose. A possible assignment θ_k is validated through a path planner, which is given the triple $(M_i(sp), M_i(gp_k), M_i(m))$, where the start pose is the goal pose of the preceding task $(M_i(sp)=M_j(gp))$, and $M_i(m)$ is a map of the environment that contains obstacles and a geofence. The obstacles correspond to circular shapes centered in the goal poses of the preceding tasks. Through the map $M_i(m)$, the path planner accounts for targets that have already been drilled prior to task M_i .

The path planner may be invoked potentially several times while solving the motion planning sub-problem. With regard to the path planner, for example, any suitable path planner can be used, e.g. a path planner for a car-like mobile robot based on cubic spirals. Such path planners are known in the art, and computes paths consisting of curvature-constrained curves constituted by few cubic spirals and straight lines. The output of the path planner is either fail, which indicates

that a particular approach angle θ_k cannot be achieved, or the spline $M_i(P)$, representing a kinematically-feasible and obstacle-free motion from $M_i(sp)$ to $M_i(gp_k)$.

Machine allocation sub-problem

5 In this sub-problem, a decision variable is a set $\mathbf{M}' \subseteq \mathbf{M}$ such that $\forall M \in \mathbf{M}', M(r)$ has not been decided, and

$\exists M_i \in \mathbf{M}' : M_i \text{ precedes } M \vee M \text{ precedes } M_i.$

That is, a total order of tasks has been decided, but machines have not yet been allocated. The values are complete
 10 assignments of machines to tasks, i.e., an assignment $M(r) = R$ for each task in $\mathbf{M}'$. The machine allocation sub-problem has a huge space of possible solutions. Each possible solution has complex ramifications on other sub-problems: different allocations will affect the amount of coordination necessary;
 15 allocations must be such that the final task of a machine is not surrounded by piles (drilled by other machines), which would make it impossible to navigate to its final parking pose.

Heuristics with high pruning (skipping) power can be used to
 20 explore the search space of this sub-problem, and these heuristics must account for other sub-problems. For example, the solver can be guided towards solutions where drill targets are assigned in rows as much as possible, e.g. least possible change in direction of the drill rig for as long rows of holes
 25 as possible, and where directions can be given regarding preferred orientations of the rows. Such data can be input e.g. by an operator. Heuristics are discussed further below. Solutions to the machine allocation sub-problem are indirectly

validated in other sub-problems, hence no particular solver is used for direct validation of possible values.

Temporal sub-problem

A task's path P is segmented into a sequence of sub-paths based on its curvature. Each segment can e.g. be associated to a convex polygon s_k resulting from the sweep of the machine's footprint along the sub-path. The resulting sequence $\{s_1, \dots, s_m\}$ of convex polygons represents the areas occupied by a machine while navigating along the path. While navigation along a line of holes can give rise to a very simple movement pattern (straight line), the movement pattern close to the geofence can be considerably more extensive. Problems become much more difficult if they contain drill targets that are close to the geofence, whereas when that is not the case problems are easier, since machines have enough space to maneuver regardless of how approach angles are chosen. This is illustrated in fig. 4C, which shows polygons representing footprints when moving from 166 of fig. 4A to 138. Obviously the movement pattern becomes considerably more complex before hole 140 of fig. 4A has been reached, which according to the example (see fig. 4B) is the first hole where the machine again is aligned with the row of holes. This is schematically illustrated in fig. 4D.

Since the path planner that is used to obtain P is aware of the obstacles created by preceding tasks, the convex polygons do not intersect piles resulting from drilling. This is illustrated in fig. 5, where black circles represent drill piles (the orientation of the drill rig is also when drilling is also indicated by arrows), polygons represent the motions of the machine. As can be seen drill piles are not touched.

In addition to the polygons representing the motion of machines, the activities involved in a task M (i.e., $M(A) = \{\text{drilling, leveling, de-leveling}\}$) have polygons associated to them. Since these activities all occur while the machine is idle in pose $M(gp)$, their polygons, in the present example, since drilling is performed substantially vertical, coincide with the polygon that covers the last sub-path of $M(P)$. Hence, the set of all convex polygons of task M is $M(S) = \{s_1, \dots, s_m\} \cup \{s_{\text{drilling}}, s_{\text{leveling}}, s_{\text{de-leveling}}\}$, where $s_{\text{drilling}} = s_{\text{leveling}} = s_{\text{de-leveling}} = s_m$.

Each convex polygon in $M(S)$ is associated to a time interval in the set $M(T) = \{I_1, \dots, I_{m+3}\}$. Interval $I_k = [I_s, I_e]$ is a flexible temporal interval within which machine $M(r)$ is in s_k , where $I_s = [l_s, u_s]$, $I_e = [l_e, u_e]$, $l_{s/e}, u_{s/e} \in \mathbb{N}$ represent, respectively, an interval of admissibility of the start and end times of the occurrence of polygon $s_k \in S$.

The temporal sub-problem consists of deciding a start and an end time for each interval I_k . The temporal sub-problem has a decision variable for every machine $R \in \mathbf{R}$.

Each decision variable is a set of tasks $\mathbf{M}' \subseteq \mathbf{M}$ such that for all $M_i \in \mathbf{M}'$:

(1) $M_i(P)$ has been decided,

(2) $M_i(r) = R$, and

(3) the start and end times of $M_i(T)$ have not been decided.

The problem of deciding valid start/end times of the intervals is reduced to a Simple Temporal Problem (STP). STP:s are well known and various algorithms exist for solving STP:s. The STP can be formulated as a collection of temporal constraints as follows.

First, for each $M_i \in \mathbf{M}'$ with intervals $M_i(T) = \{I_1, \dots, I_{m+3}\}$, temporal constraints that reflect the order of the convex polygons along the path $M_i(P)$ are imposed:

$$I_{k-1} \text{ before } I_k, k \in \{2 \dots m+3\}. \quad (1)$$

Second, temporal constraints that force the possible start and end times of tasks to adhere to the ordering decided by the sequencing solver are added. That is, for each pair of tasks $(M_i, M_j) \in \mathbf{M}' \times \mathbf{M}'$ that are subject to a sequencing constraint M_i precedes M_j , the following temporal constraint is added among the intervals $M_i(T) = \{I_1^i, \dots, I_{m+3}^i\}$ and $M_j(T) = \{I_1^j, \dots, I_{m+3}^j\}$:

$$I_{m+3}^i \text{ before } I_1^j, \quad (2)$$

reflecting the fact that the de-leveling polygon of task M_i occurs before the first motion of task M_j . Third, we impose minimum durations of the motions and activities of the machines:

$$\text{Duration}[\alpha, \infty) \quad I_k, k \in \{1 \dots m+3\}. \quad (3)$$

For every motion polygon $s_k, k \in \{1, \dots, m\}$, an initial value for α is computed based on the maximum allowed velocity of machine R. Hence, the earliest time solution of the STP represents the fastest possible execution of all motions and activities in

the plan, i.e., an “optimistic” estimate of the start and end times of all operations of all machines.

During execution, further temporal constraints can be added to reflect contingencies such as machine maintenance, delays, and so on. The association of an interval per polygon allows predication via temporal constraints how long every movement or activity will take. Solving the STP is polynomial in the number of intervals in the temporal problem, namely $\sum_{M_i \in M'} |M_i(T)|$.

Note that there are no temporal constraints among intervals pertaining to different machines, the motions and activities of different machines may be concurrent.

Coordination sub-problem

Since a plurality machines operate in the same environment, it is crucial to address collision/deadlock avoidance. As a consequence of decisions made in all previous sub-problems, the common constraint network includes polygons, temporal intervals, and temporal constraints (eqs. (1) to (3)) among them. The STP solver computes start and end times for each interval. This determines when machines will occupy motion and activity polygons in the various tasks. If two polygons pertaining to different vehicles overlap, and their corresponding temporal intervals intersect, then the two vehicles may collide. Coordination avoids this by imposing additional constraints that eliminate temporal intersection where needed.

Decision variables of the coordination sub-problem are pairs of polygons and intervals represented by quadruple $(s_k^i, s_m^j, l_k^i,$

I_m^j), of tasks i and j respectively, that overlap both spatially and temporally, i.e., $s_k^i \cap s_m^j \neq \emptyset \wedge I_k^i \cap I_m^j \neq \emptyset \wedge M_i(R) \neq M_j(R)$.

The value of a decision variable is one of two possible constraints $\{I_k^i \text{ before } I_m^j, I_m^j \text{ before } I_k^i\}$, imposing either of which eliminates the temporal overlap between concurrent polygons. The STP solver will validate the sequencing in time of these two overlapping polygons accordingly. It will also compute the consequent shift in the occurrence of any other polygon whose interval is constrained with I_m^j or I_k^i by means of temporal constraint propagation within the common constraint network.

The polygons involved in the decision variables represent two types of occupancy. The first type corresponds to the motions of machines as described above. The second corresponds to the piles created by drilling. By modeling both types of polygons in the common constraint network, collisions among machines and with piles are found and thus scheduled. This is exemplified in fig. 7, where there machines 701, 702, 703 each drills two rows of holes 704-705, 706-707, and 708-709, respectively. As can be seen from fig. 7, motions of machine 701 partly occupy rows 706 and 707 for maneuvering between rows 704 and 705. This results in machine 702 having to wait just before the conflicting area, until machine 701 finishes its maneuver. According to the disclosed example, machine 702 will occupy some part of rows 708, 709, and hence machine 703 will have to wait until machines 701, 702 are finished switching rows. The motion planner can ensure that the motions of machine 702 do not conflict with rows 704 and 705 and hence do not disturb already drilled holes of these rows is handled by the motion planner. This also applies for machine 703 and rows 706, 707. As machines start their execution concurrently,

their motions would lead to collisions, were it not for the fact that the coordination sub-problem was solved as well. The temporal constraints can force machines 702 and 703 to yield when necessary.

5 Backtracking search

The collection of decision variables for each sub-problem mentioned above constitutes the high-level CSP (henceforth called meta-CSP). Search in the meta-CSP consists in finding an assignment of values to decision variables that represent
10 high-level requirements. Each of these requirements is, in this case, a sub-problem. Possible values among which these assignments are selected are verified by a specific solver for each sub-problem. Thanks to the common representation of the search space, each sub-problem solver accounts for the
15 assignments made for decision variables of other sub-problems. For example, the path planner validates with respect to a map containing obstacles resulting from sequencing decisions; and the coordinator's decisions depend on the machine allocation as well as motion plans.

20 The choices of values for decision variables in the various sub-problems contribute parts of the tasks in the common representation, and the sub-problem solvers propagate the consequence of these decisions. The sub-problem solvers used in the present approach are denoted in the following with
25 solve- p , where $p \in \{\text{seq}, \text{alloc}, \text{time}, \text{coord}, \text{mp}\}$.

As has been explained, solve-seq disallows sequencing decisions that are not totally ordered; solve-mp verifies by means of a motion planner that motions are kinematically feasible and obstacle-free; solve-alloc accepts all candidate
30 allocations, as the infeasible ones are discovered indirectly

via coordination; solve-time is a STP solver which computes feasible start/end times of task intervals subject to temporal constraints; solve-coord is also provided by the same STP solver, which validates and computes the consequences of temporal ordering decisions.

A CSP-style heuristically guided backtracking search can be used to find values to assign to the decision variables. As is well known, backtracking algorithms are frequently used in solving CSP problems. Henceforth, let the set of sub-problems be indicated by

Function $DP^3\text{-solver}(\mathcal{M})$: success or failure

```

1   $D_{seq} \cup D_{alloc} \cup D_{time} \cup D_{coord} \cup D_{mp} \leftarrow \text{CollectDVars}(\mathcal{M})$ 
2  if  $\exists D_i \neq \emptyset, i \in \{seq, alloc, time, coord, mp\}$  then
3       $p \leftarrow \text{Choose}(\{seq, alloc, time, coord, mp\}, h_{prob})$ 
4       $d \leftarrow \text{Choose}(D_p, h_i^{seq})$ 
5       $V_d \leftarrow \text{CollectValues}(d)$ 
6      while  $V_d \neq \emptyset$  do
7           $v \leftarrow \text{Choose}(V_d, h_i^{val})$ 
8          Update( $\mathcal{M}, v$ )
9          if Solve- $p(\mathcal{M})$  then
10             return  $DP^3\text{-solver}(\mathcal{M})$ 
11             Remove( $\mathcal{M}, v$ )
12              $V_d \leftarrow V_d \setminus v$ 
13     return failure
14 return success
```

Given the set of tasks $\mathbf{M}$, Algorithm $DP^3\text{-solver}$ collects all the decision variables belonging to all the sub-problems (line 1), and terminates when no decision variables are left (lines 2 and 14). A particular sub-problem is then chosen according to a sub-problem ranking heuristic h_{prob} (line 3), e.g., h_{prob} prioritizes machine allocation decision variables over coordination decision variables, as the latter problem

requires machines to be assigned to tasks (see above). Among the decision variables of a sub-problem, one is chosen according to a variable ordering heuristic h_i^{var} (line 4). For example, which target should be selected first among the decision variables D_{mp} of the motion planning sub-problem. Among possible alternative values, one is chosen according to value ordering heuristic h_i^{val} (lines 5- 7). For instance, which approach angle has to be selected for a given target in the motion planning sub-problem. This value is added to the common representation (line 8). The sub-problem solver solve-p verifies that the assignment v is feasible. If so, DP3-solver is called recursively (line 10), which results in selecting another unassigned variable subject to the newly updated common representation **M**. Note that if all possible values are attempted for a decision variable d and all are rejected by solve-p, the algorithm returns failure (lines 6,11-13). The problem-, variable- and value-ordering heuristics used in the DP3-solver are explained in the following.

Heuristics

The DP3-solver must select a set of decision variables pertaining to a sub-problem from the union of all decision variables. This selection can be guided by a heuristic h_{prob} to improve computational efficiency. Let $D_i < D_j$ indicate that the decision variables of problem i have a higher priority than those of problem j . The partial ordering based on which the h_{prob} heuristic operates is $\{D_{\text{seq}} < D_{\text{aloc}} < D_{\text{tp}} < D_{\text{coord}}, D_{\text{mp}} < D_{\text{aloc}} < D_{\text{tp}} < D_{\text{coord}}\}$. Decision variables to branch on (within a chosen D_i) are ordered based on h_{var} , and alternative values are chosen according to h_{val} . Variable ordering heuristics are

provided for the sequencing sub-problem and for the coordination sub-problem. The latter heuristic is based on temporal flexibility and has been used in the prior art for resource-constrained project scheduling. The former is based on an analysis of the drill target placements, and is described below.

Variable Ordering for Sequencing h_{seq}^{var}

The pattern of drill targets is analyzed to reveal its topology and the possible principal directions of drill target sequencing. For other kinds of mining tasks to be performed, similar analysis can be performed. To determine the former, a distance threshold is used; the latter are discovered via a K-Means which is a heuristic algorithm used to cluster the set of angular coefficients of topologically neighboring drill targets. This yields clusters containing similarly oriented edges of the topology. These are used to group drill targets into roughly-parallel lines. The topology and the groupings are used to rank drill targets in groups. Variable in these groups are first in the sequencing sub-problems.

Value ordering heuristics are defined for the sequencing, allocation, motion planning, and coordination sub-problems. As for variable ordering, the decision variables in the coordination sub-problem are branched upon using a heuristic based on temporal flexibility that is widely used in the scheduling literature. The remaining heuristics h_{seq}^{val} , h_{alloc}^{val} are explained below.

Value Ordering for Sequencing h_{seq}^{val}

A value for a decision variable of the sequencing sub-problem decides which drill target precedes a given target. There are

many alternatives for this choice. Note that sequencing decision variables that are resolved first are those pertaining to drill targets along groups – for such decision variables, the heuristic prioritizes one of two possible predecessors, namely those adjacent to the current decision variable in the grouping.

For example, the two values with highest heuristic score for decision variable M_{140} in Figure 4A are M_{141} precedes M_{140} and M_{139} precedes M_{140} .

Also, this heuristic contributes to alleviating the computational burden of finding sequences in regions close to the geofence while transitioning between groups. Finding a feasible sequence in these situations is challenging because a machine has limited space to maneuver. These regions of highly-constrained motion span typically eight targets for every pair of adjacent groups, thus in the worst case sequencing requires verifying, through motion planning, 8^7 possible motions for each pair. For this reason, the heuristic may use given sequence patterns that reflect common practice by human operators. A sequence pattern is a topological description of a human driving behavior, augmented with metric information that facilitates assessing whether the pattern is applicable in a given region. Specifically, a sequence pattern is a graph (V, E) where V is a set of nodes representing drill targets, and E is a sequence of precedence constraints among the nodes. A distance threshold d_{geofence} is also given, and represents the minimum distance to the geofence required for the pattern to hold. Also, a ranking $<$ of the nodes in terms of how far they lie from the geofence may be provided. An example pattern that can be used by the solver is shown in Figure 6. If the search is considering a decision variable M_i ,

that is surrounded by targets that can be mapped to the nodes in the pattern, then the heuristic ranks possible predecessors of M_i according to the edges in E . Suitable patterns can be defined and used by the solver to improve computational efficiency.

Value Ordering for Motion Planning h_{mp}^{val} .

This heuristic may e.g. suggest approach angles for a target that is similar to those assigned to other drill targets in a same group.

Value Ordering for Machine Allocation h_{alloc}^{val} . A solution to the machine allocation sub-problem determines which drill target is drilled by which machine. Among all possible choices, those may be preferred which have three properties: (1) each machine is assigned to a contiguous sequence; (2) start and end tasks of a contiguous sequences are the drill targets close to an open area, i.e., not close to a geofence and not those that are entirely surrounded by other drill targets; and (3) targets are evenly distributed among machines or according to machine capacity when machines of different capacity are used. This heuristic not only contributes to the plan quality in terms of similarity to what a human planner would decide, but also improves the efficiency in planning time by suggesting a restriction on start and exit points for each machine.

The use of heuristics e.g. according to the above may substantially improve computational efficiency when seeking a solution to the problem of assigning the tasks to the machines.

Adapting solutions during operation

Several aspects of the overall problem of assigning tasks become known only online. Therefore it may be necessary to compute at least parts of the solution to the overall problem during execution, i.e. during drilling according the present example, and/or to adapt existing plans to contingencies.

For example, the actual durations of activities only become apparent during execution. In a bench, various types of contingencies may occur, such as unexpected maintenance of machines, or increased drilling time due to unknown geological characteristics of the terrain. Therefore, it may be required to monitor the execution of the tasks and reflect the contingencies in the common representation. According to the present example, the nominal behavior of the machines is given by a solution of the DP3, obtained via Algorithm above.

The start and end times associated to the intervals $M(T)$ of every task M are computed through temporal propagation. All the lower bounds represent the earliest possible times at which tasks can be executed, and are used to compute the desired speeds at which the computed paths should be driven by the vehicle executives. The control unit 206 controls the the machine to follow the given trajectories. It also reports current progress of the machine. Deviations are used as constraints by the STP solver to propagate any mismatch between prescribed and executed tasks of all machines being used. The STP solver plays a central role in execution monitoring. The common representation of the tasks can be updated e.g. at a frequency of 1Hz to continuously account for deviations. A task is ended by adding a temporal constraint into the common constraint network representing the finish time of the task as the executive layer informs. The consequences of such updates can be easily computed within the

period of one second because the STP solver performs polynomial inference. Also, due to the fact that adding constraints cannot “undo” other decisions, unforeseen durations (e.g., encountering hard rock while drilling) can be accounted for at execution time.

More precisely, the prolongation of an activity represented by a flexible time interval associated to a motion polygon will not affect the sequencing, the approach angle, the particular motions, nor machine allocations. It only bears consequences on the coordination sub-problem, as delays may need to be propagated to other waiting machines.

According to one embodiment, e.g. if it is crucial to minimize the Time To Completion TTC, prolongation of an activity may be allowed lead to the re-allocation of the machines, which in turn would result in updating the decisions in the sequencing sub-problems. This allows for re-balancing the workload among the machines.

The feedback of progress data may also be utilized when only one machine is operating, also when the machine is manually operated, since this still will facilitate planning of further work in the mine. Also, rearrangement of tasks may be required also in this case, e.g. if another machine is taken into operation.

On-line temporal reasoning also caters to another important requirement of mining companies, namely the need to know an estimate of the Time to Completion (TTC) in order to plan following events and/or resource usage. At planning time, an optimistic TTC can be calculated by initializing the duration constraints with reasonable values: the durations of intervals corresponding to motion polygons are computed using the

maximum allowed speed of machines; and the intervals corresponding to activity polygons are initialized with durations under nominal conditions (average rock density, and no maintenance). As execution proceeds, TTC is updated as a result of temporal reasoning to reflect the actual situation, which facilitates planning of other activities in the mine.

The time of completion, i.e. the point of time at which the tasks are expected to be carried out can be displayed and updated e.g. to an operator. Alternatively or in addition, a time to completion can be displayed, i.e. the time remaining to complete the tasks.

According to the invention, the overall problem is divided into a plurality of sub-problems and the mutually feasible solutions to the individual sub-problems are found.

The DP3-solver combines solutions from different sub-problems, each of which can be seen as a "classical" robotics problem. A given hybrid problem is broken down and interdependencies among sub-problems are identified. A heuristically guided backtracking search can be used to find a solution to the overall problem in the joint search spaces of the sub-problems.

Furthermore, a plurality of solutions to the overall problem of assigning tasks and/or one or more sub-problems can be found. In such situations a solution can be selected on the basis of a cost function, where the cost function can take any suitable parameter into account. For example, the cost function can constitute minimization of a time to completion of said set of tasks.

The invention has so far been described in connection to a surface mine. The invention, however, is suitable for any

mining application where a plurality of movable machines can be employed to autonomously perform tasks, such as e.g. collection of ore from one location to another, e.g. in underground mines.

- 5 Consequently, the invention is not limited other than in regard of what is stated in the appended claims.

CLAIMS

1. Method for assigning a set of tasks to a plurality of drill rigs (200A, 200B;701-703), said tasks including drilling of holes by said plurality of drill rigs (200A, 200B;701-703),

5 **characterized in** that the method includes:

- defining a first set of constraints to be fulfilled when assigning tasks to said plurality of drill rigs (200A, 200B;701-703);

10 - finding an overall solution fulfilling said first set of constraints by solving each constraint as a sub-problem, a solution to at least one sub-problem being dependent on the solution of at least one other sub-problem;

15 - said overall solution fulfilling said first set of constraints being an overall solution where a solution to a first of said sub-problems is validated by solutions of others of said sub-problems, and

20 - assigning tasks to said plurality of drill rigs (200A, 200B;701-703) according to the determined validated solution, wherein tasks of said set of tasks are arranged to be carried out at least partially overlapping in time by said plurality of drill rigs (200A, 200B;701-703).

25 2. Method according to claim 1, wherein said tasks to be carried out by said plurality of drill rigs include drilling of holes and maneuvering the drill rigs between holes to be drilled.

3. Method according to any one of claims 1-2, further including:

- validating a solution to said first sub-problem by determining that said solution to said first sub-problem

30 allows a solution of other sub-problems being dependent on the solution to said first sub-problem.

4. Method according to any one of claims 1-3, wherein said plurality of drill rigs (200A, 200B; 701-703) are arranged to be autonomously driven between positions for drilling of holes, and autonomously carrying out tasks assigned to the plurality of drill rigs, respectively.

5. Method according to any one of claims 1-4, further including:

- utilizing a common representation of said sub-problems, where said tasks are represented by variables, so that solver algorithms of the sub-problems, respectively, share a common search space when searching a solution to a sub-problem.

6. Method according to any one of claims 1-5, further including:

- assigning priorities to said sub-problems, and determining a solution to the assigning of said tasks by validating a solution to a higher prioritized sub-problem by solutions to lower prioritized solutions.

7. Method according to any one of the preceding claims, wherein a solution to said first sub-problem is discarded when solutions to other sub-problems validating the first sub-problem cannot be found.

8. Method according to any one of the preceding claims, further including:

- discarding solutions to said first sub-problem when said solutions to said first sub-problem is not validated by solution to all sub-problems being dependent on the solution to the first sub-problem.

9. Method according to any one of the preceding claims, wherein solving of at least one of said sub-problems require an

already present solution of at least one other of said sub-problems.

10. Method according to any one of the preceding claims, further including:

- 5 - solving said problem of assigning said tasks using a representation of holes to be drilled by means of said plurality of drill rigs, and a representation of said plurality of drill rigs.

11. Method according to any one of the preceding claims, wherein said tasks include drilling of holes arranged to be drilled within a confined geographical area, said plurality of drill rigs being assigned tasks of said set of tasks being allowed to move within overlapping portions of said geographical area.

15 **12.** Method according to any one of the preceding claims, further including:

- assigning tasks involving a first set of holes to be drilled to a first drill rig, and tasks involving a second set of holes to be drilled to a second drill rig, the assignment of tasks being such that at least two of said rigs will pass same position at different points in time.

13. Method according to any one of the preceding claims, said tasks including a plurality of holes to be drilled wherein:

25 - one of said sub-problems consists of determining a sequence of drilling said holes such that each of said holes to be drilled is sequenced with respect to the other holes to be drilled.

14. Method according to claim 13, said sub-problem of sequencing holes to be drilled being said first sub-problem to be solved among said sub-problems.

15. Method according to any one of the preceding claims,
5 further including:

- determining a start time and an end time for each task,
start time and end time of a task being defined in relation to
start times and end times of times for others of said tasks,
and said assignment of tasks including a start time and end
10 time for each of said tasks, respectively.

16. Method according to claim 15, further including:

- receiving progress data regarding progress of drilling of
holes from said plurality of drill rigs, and recalculating
said start times and end times for tasks including holes
15 remaining to be drilled on the basis of received progress
data.

17. Method according to any one of the preceding claims:

- one of said sub-problems being a coordination sub-problem
scheduling the plurality of drill rigs such that when said
20 drill rigs are operating in overlapping portions of said
geographical area, times for performing said tasks are
assigned such that said drill rigs will not collide.

18. Method according to any one of said claims, further
including:

25 - determining an estimated time of completion and/or time to
completion of said tasks, and displaying said estimated time
of completion and/or time to completion.

19. Method according to claim 18, further including:

- updating said estimated time of completion and/or time to
30 completion of the tasks on the basis of progress data received

from said plurality of drill rigs when drilling carrying out said tasks.

20. Method according to any one of the preceding claims, further including, when carrying out said tasks, said plurality of drill rigs communicating progress regarding fulfillment of said tasks, and

- re-solving the assignment of tasks to said plurality of drill rigs when data from said plurality of drill rigs indicate a requirement of re-assignment of said tasks.

21. Method according to any one of the preceding claims, further including, when solving said problem of assigning tasks to said plurality of drill rigs:

- determine the assigning of said tasks such that, when said drill rig has finished assigned tasks, a defined end position can be reached by a drill rig without violating allowed movements within the area in which said tasks are being carried out.

22. Method according to any one of the preceding claims, further including:

- assigning tasks to said plurality of drill rigs only if a solution to said first sub-problem is validated.

23. Method according to any one of the preceding claims, wherein:

- one of said sub-problems consists of determining movement of said plurality of drill rigs and/or space required to traverse when moving from drilled holes to holes to be drilled.

24. Method according to claim 23, further including:

- determining a pattern of movement of said plurality of drill rigs such that holes can be drilled without disturbing piles of drill cuttings of already drilled holes.

25. Method according to claim 23 or 24 further including:

- when determining pattern of movement of said drill rig, determining a pattern such that the drill rig can move away from a drilled hole without crossing a border defining said geographical area.

26. Method according to any one of the preceding claims, further including:

- restricting the number of allowed angular directions of said plurality of drill rigs determining alignment for drilling a hole to a first set of angles with respect to a reference direction, said first set of angles being a number of angles in any of the intervals 4-90, 4-50, 4-20.

27. Method according to any one of the preceding claims, further including:

- determining when the plurality of drill rigs are to carry out motion, drilling, leveling and de-leveling operations subject to temporal constraints by coordinating drilling by said plurality of drill rigs.

28. Method according to any of the preceding claims, further including, when tasks have been assigned to a drill rig:

- communicating said tasks to said drill rig.

29. Method according to any of the preceding claims, further including, when a plurality of solutions to the assignment of tasks and/or a sub-problem is found, selecting solution on the basis of a cost function.

30. Methods according to claim 26, where the cost function is a time to completion of said set of tasks.

31. Method according to any one of the preceding claims, further including:

- by means of said plurality of drill rigs, carrying out tasks assigned to said plurality of drill rigs.

5 32. System for assigning a set of tasks to a plurality of drill rigs (200A, 200B;701-703), said tasks including drilling of holes by said plurality of drill rigs (200A, 200B;701-703), **characterized in** that the system includes:

10 - receiving means for receiving a first set of constraints to be fulfilled when assigning tasks to said plurality of drill rigs (200A, 200B;701-703);

15 - solving means for finding an overall solution fulfilling said first set of constraints by solving each constraint as a sub-problem, a solution to at least one sub-problem being dependent on the solution of at least one other sub-problem, said overall solution fulfilling said first set of constraints being an overall solution where a solution to a first of said sub-problems is validated by solutions of others of said sub-problems, and

20 - assigning tasks to said a plurality of drill rigs (200A, 200B;701-703) according to the determined validated overall solution, wherein tasks of said set of tasks are arranged to be carried out at least partially overlapping in time by said plurality of drilling rigs (200A, 200B;701-703).

25 33. Drill rig (200A, 200B;701-703), **characterized in** that it comprises a system according to claim 29.

Fig. 1

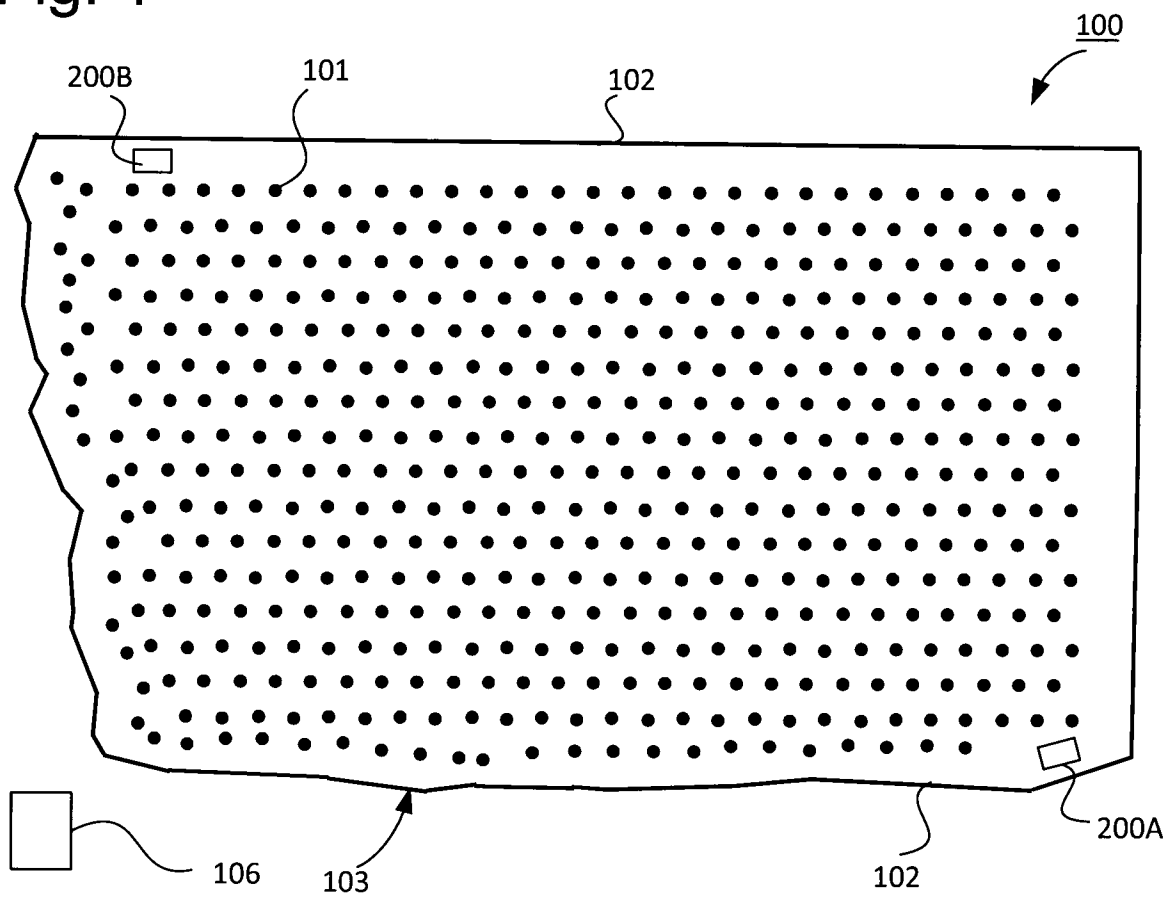


Fig. 2

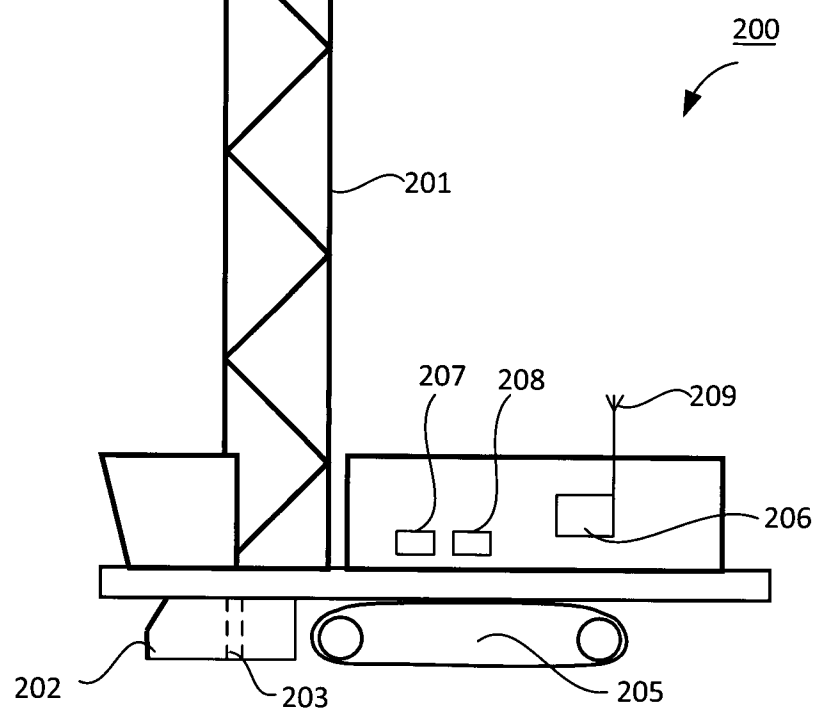
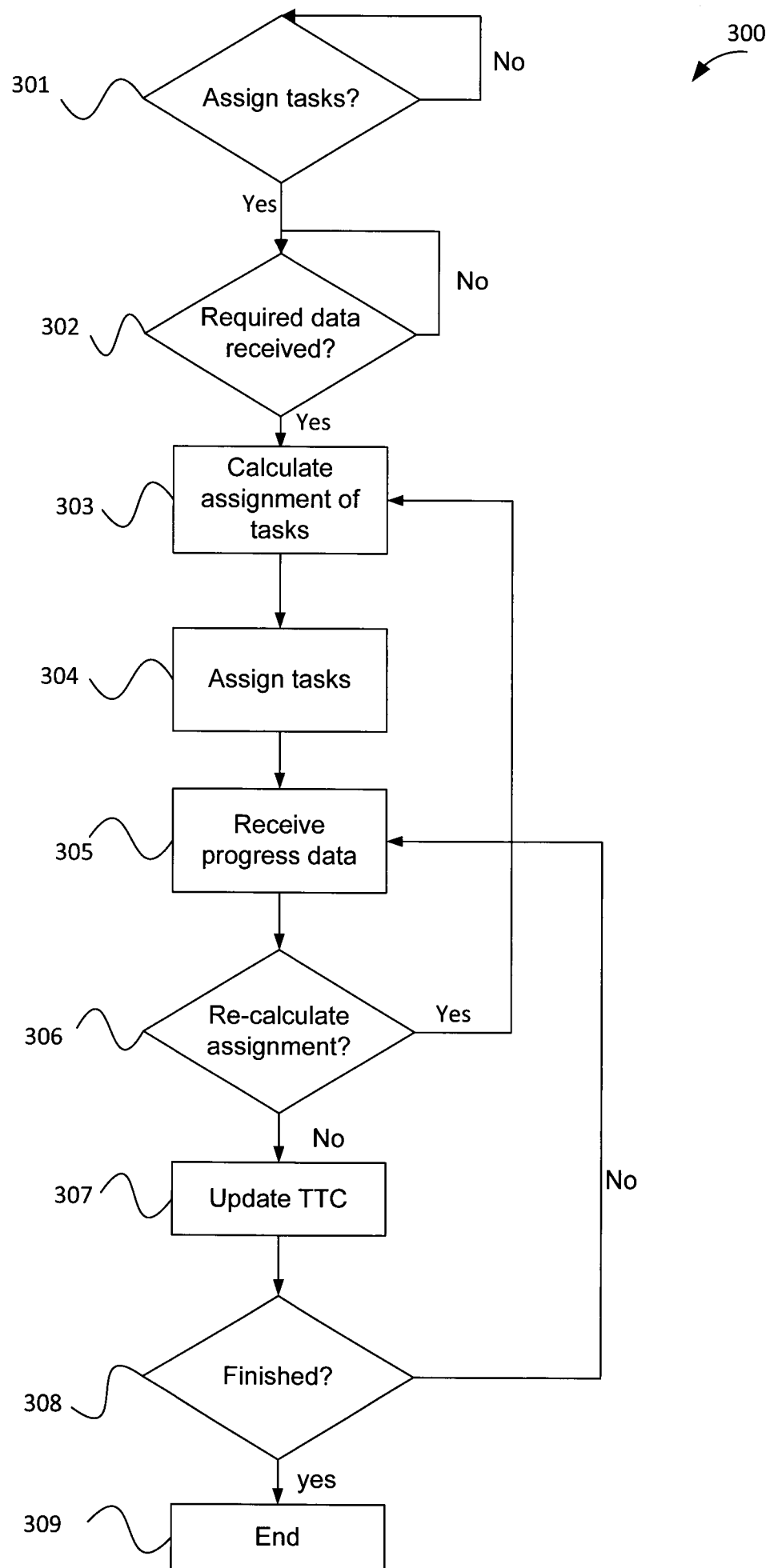


Fig. 3



3/6

Fig. 4A

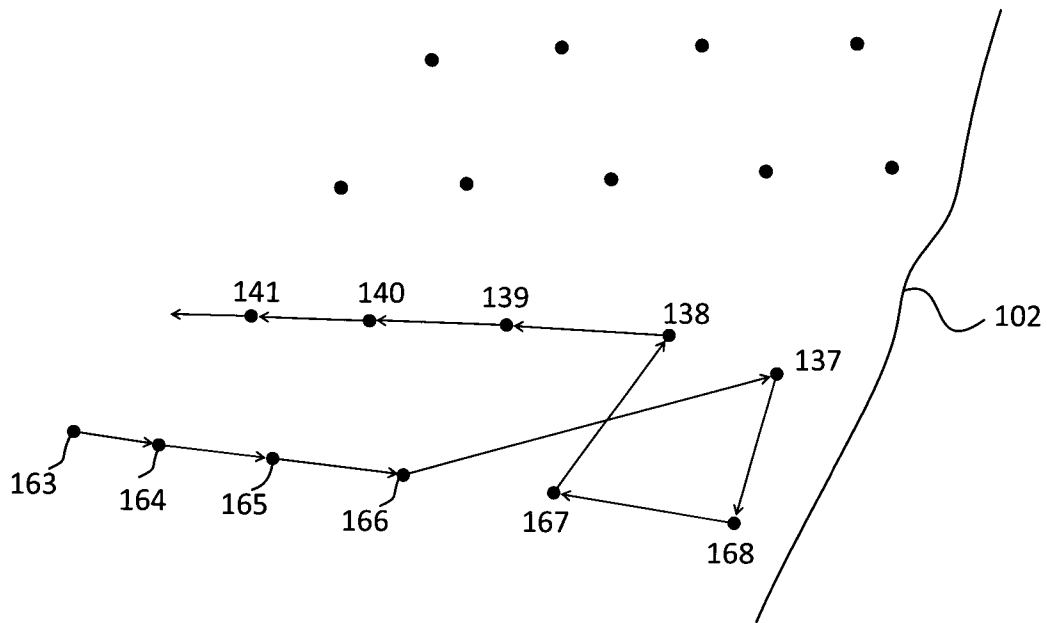
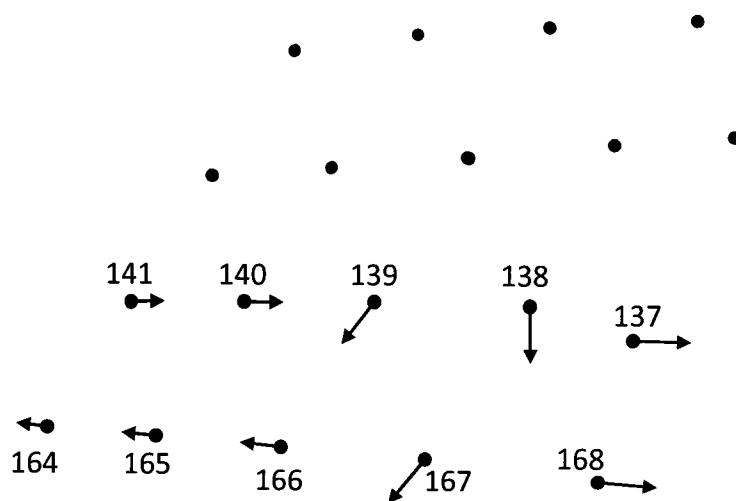


Fig. 4B



4/6

Fig. 4C

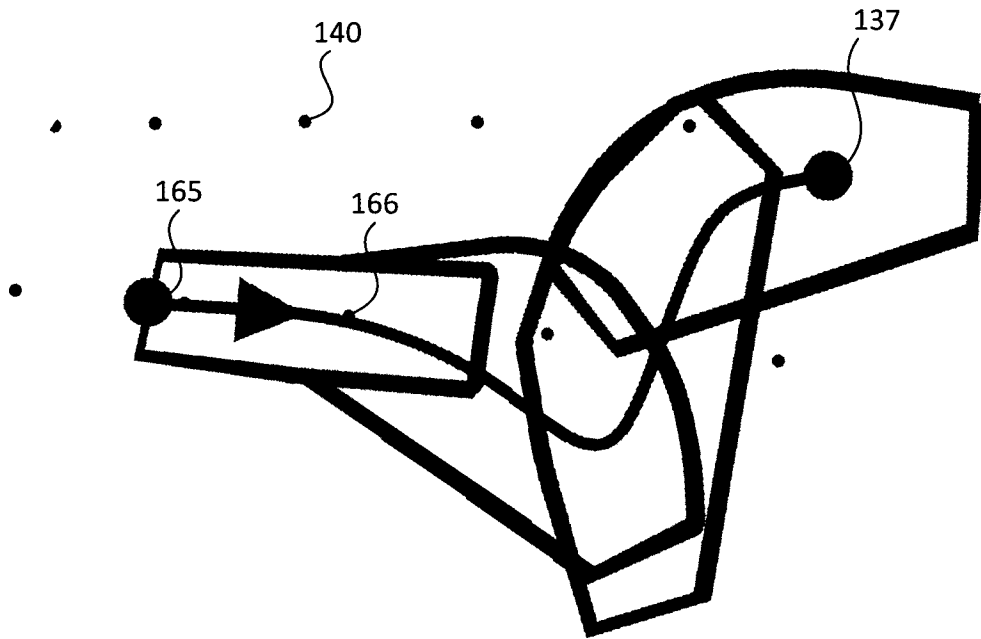


Fig. 4D

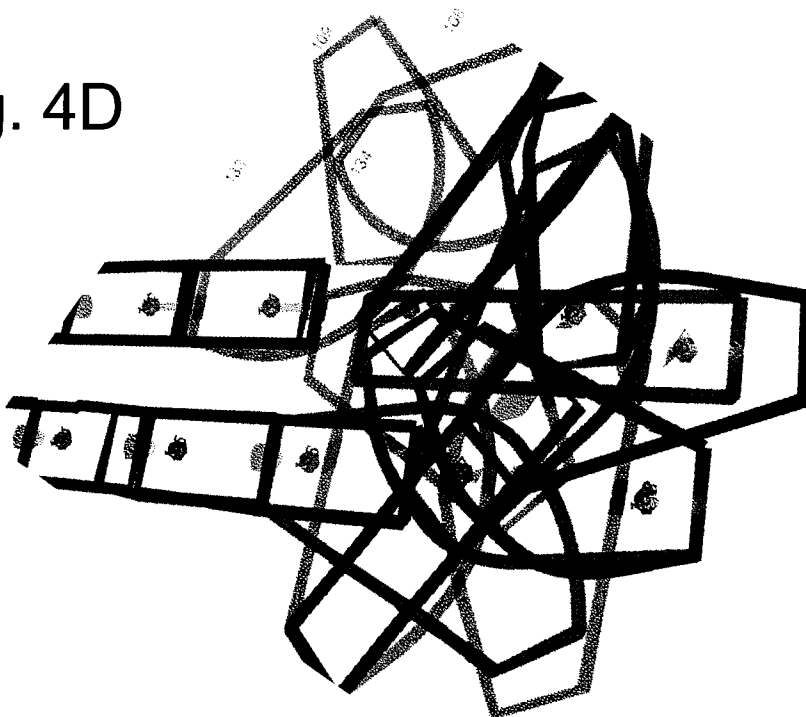


Fig. 5

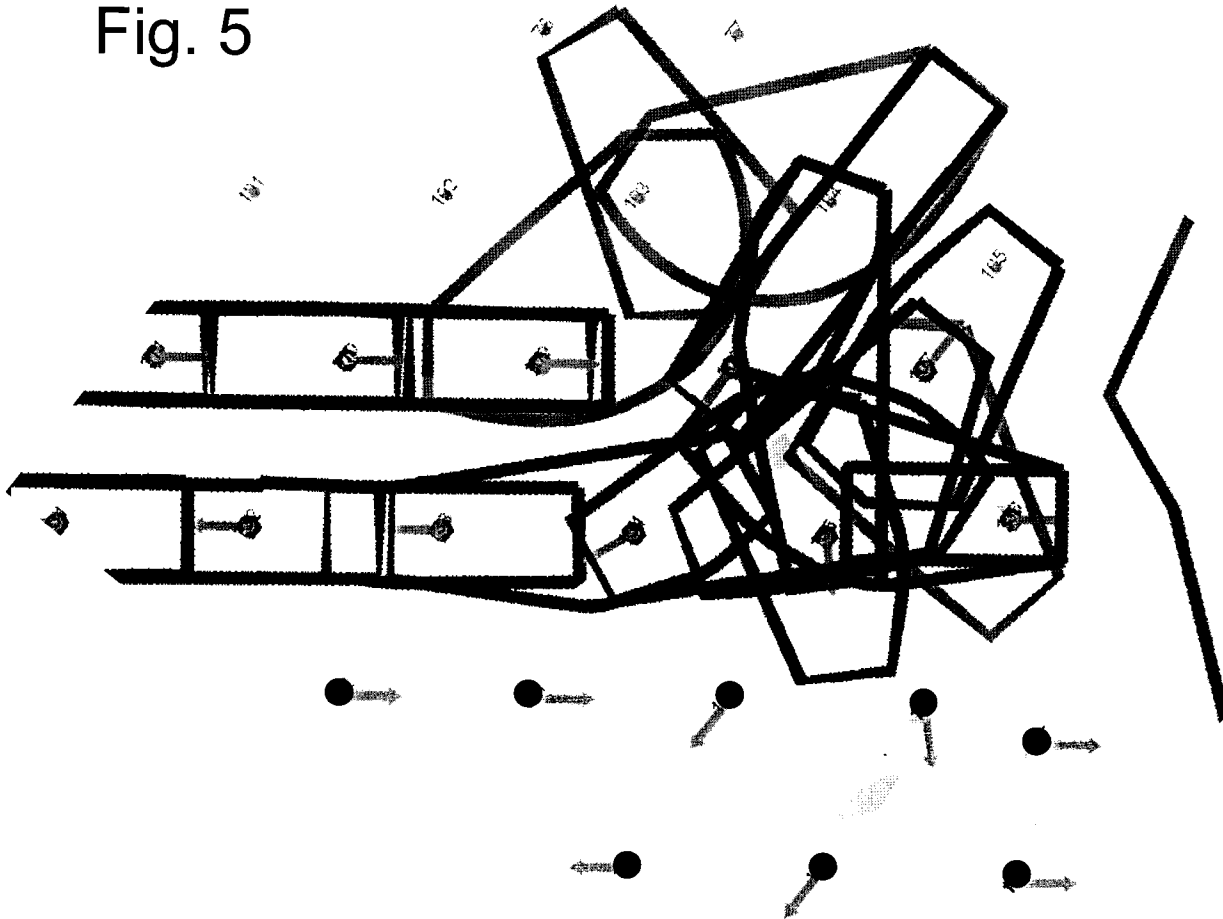
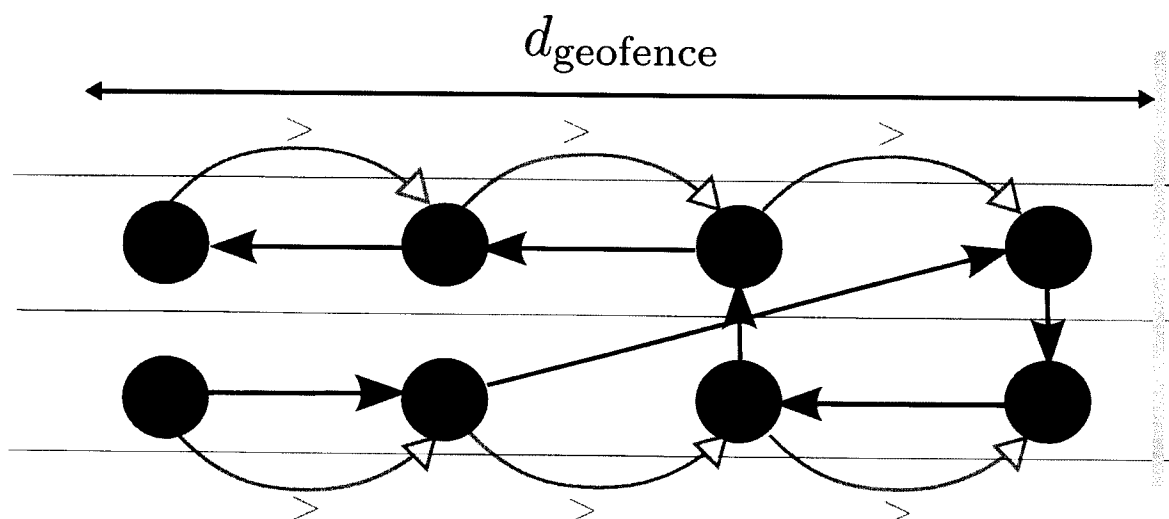
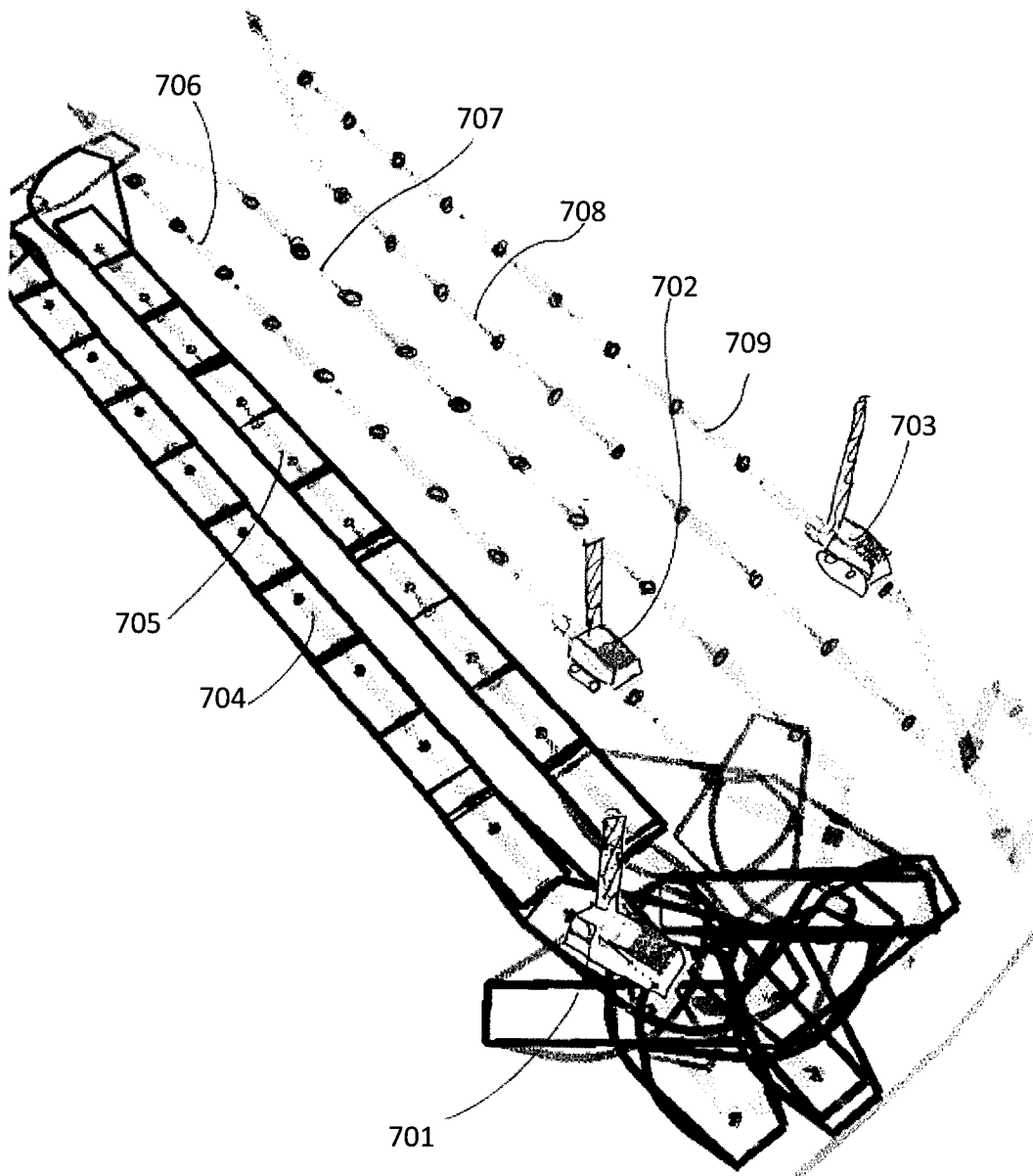


Fig. 6



6/6

Fig. 7



INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE2016/050924

A. CLASSIFICATION OF SUBJECT MATTER

IPC: see extra sheet

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: E21B, G05D, G06Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE, DK, FI, NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, PAJ, WPI data, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2010118470 A1 (UNIV SYDNEY ET AL), 21 October 2010 (2010-10-21); abstract; page 1, line 5 - page 1, line 6; page 1, line 18 - page 1, line 21; page 3, line 5 - page 3, line 9; page 3, line 14 - page 3, line 18; page 7, line 18 - page 7, line 20; page 9, line 5 - page 9, line 17; page 10, line 15 - page 10, line 20; page 10, line 24 - page 10, line 27; page 11, line 8 - page 11, line 16; page 12, line 26 - page 12, line 29; page 13, line 1 - page 13, line 20; page 13, line 24 - page 13, line 27; page 19, line 19 - page 19, line 27; page 20, line 9 - page 20, line 10; page 22, line 1 - page 22, line 4; page 25, line 9 - page 25, line 12; page 25, line 19 - page 25, line 27; figures 4,7 --	1-33



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

“A” document defining the general state of the art which is not considered to be of particular relevance

“E” earlier application or patent but published on or after the international filing date

“L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

“O” document referring to an oral disclosure, use, exhibition or other means

“P” document published prior to the international filing date but later than the priority date claimed

“T”

later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

“X”

document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

“Y”

document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

“&”

document member of the same patent family

Date of the actual completion of the international search

19-12-2016

Date of mailing of the international search report

19-12-2016

Name and mailing address of the ISA/SE

Patent- och registreringsverket

Box 5055

S-102 42 STOCKHOLM

Facsimile No. + 46 8 666 02 86

Authorized officer

Cao Cao

Telephone No. + 46 8 782 28 00

INTERNATIONAL SEARCH REPORT

 International application No.
 PCT/SE2016/050924

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2011032208 A1 (UNIV SYDNEY ET AL), 24 March 2011 (2011-03-24); abstract; page 1, line 5 - page 1, line 7; page 3, line 7 - page 3, line 32; page 4, line 31 - page 4, line 33; page 5, line 21 - page 5, line 27; page 6, line 14 - page 6, line 18; page 9, line 5 - page 9, line 8; page 9, line 15 - page 9, line 23; page 11, line 24 - page 11, line 29; page 12, line 7 - page 12, line 12; page 14, line 31 - page 15, line 1; page 17, line 29 - page 19, line 1; page 19, line 27 - page 19, line 30; page 22, line 1 - page 22, line 2; page 27, line 20 - page 27, line 23; page 30, line 13 - page 30, line 15; page 30, line 32 - page 31, line 4; figures 1-14, 16, 18 --	1
A	WO 2010124340 A1 (UNIV SYDNEY ET AL), 4 November 2010 (2010-11-04); abstract; page 19, line 7 - page 19, line 10; page 21, line 6 - page 21, line 19; page 23, line 10 - page 23, line 21 --	1-33
A	US 20150170087 A1 (JOHNSTON LUCIAN ET AL), 18 June 2015 (2015-06-18); abstract; paragraphs [0008], [0027], [0034]-[0037] --	1-33
A	US 20070027612 A1 (BARFOOT TIMOTHY D ET AL), 1 February 2007 (2007-02-01); abstract; paragraphs [0005], [0083], [0105]-[0107] --	1-33
A	US 20050209836 A1 (KLUMPEN HANS E ET AL), 22 September 2005 (2005-09-22); abstract; paragraphs [0006], [0091], [0112], [1296]-[1297] --	1-33
A	"Multi-Goal Planning for an Autonomous Blasthole Drill", Pantelis Elinas, Proceedings of the Nineteenth International Conference on Automated Planning and Scheduling, 2009; whole document; abstract -- -----	1-33

Continuation of: second sheet

International Patent Classification (IPC)

G06Q 10/04 (2012.01)

E21B 44/00 (2006.01)

G05D 1/02 (2006.01)

G06Q 10/06 (2012.01)

G06Q 50/02 (2012.01)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SE2016/050924

WO	2010118470 A1	21/10/2010	AU	2010237608 B2	25/06/2015
			CA	2758744 A1	21/10/2010
			US	9129236 B2	08/09/2015
			US	20120024605 A1	02/02/2012
WO	2011032208 A1	24/03/2011	AU	2010295227 B2	05/02/2015
			CA	2774163 A1	24/03/2011
			US	8612084 B2	17/12/2013
			US	20120179322 A1	12/07/2012
WO	2010124340 A1	04/11/2010	AU	2010242545 A2	01/12/2011
			BR	PI1010871 A2	15/03/2016
			CA	2760673 A1	04/11/2010
			PE	10212012 A1	19/08/2012
			US	20120046818 A1	23/02/2012
			US	9476303 B2	25/10/2016
US	20150170087 A1	18/06/2015	NONE		
US	20070027612 A1	01/02/2007	AT	504872 T	15/04/2011
			AU	2006274420 A1	01/02/2007
			AU	2011202456 B2	02/08/2012
			AU	2006274421 B2	11/08/2011
			CA	2612921 A1	01/02/2007
			CA	2616613 A1	01/02/2007
			DE	602006021188 D1	19/05/2011
			EP	1913235 A4	11/11/2009
			EP	1924981 B1	12/09/2012
			EP	2450763 A1	09/05/2012
			US	7756615 B2	13/07/2010
			US	8260483 B2	04/09/2012
			US	8090491 B2	03/01/2012
			US	20120035798 A1	09/02/2012
			US	20090043439 A1	12/02/2009
			WO	2007012198 A1	01/02/2007
			WO	2007012199 A3	27/03/2008
			ZA	200801764 B	26/11/2008
			ZA	200800635 B	26/11/2008

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SE2016/050924

US	20050209836 A1	22/09/2005	AR	048585 A1	10/05/2006
			CA	2560275 A1	29/09/2005
			EA	010003 B1	30/06/2008
			EA	200601713 A1	29/06/2007
			EP	1730613 A1	13/12/2006
			MX	PA06010580 A	15/03/2007
			NO	20064177 A	18/12/2006
			TW	I305316 B	11/01/2009
			US	7539625 B2	26/05/2009
			WO	2005091096 A1	29/09/2005
