Remote control and monitoring of an underground robotic drilling equipment for landfill remediation

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***Abstract*— Pollution control and landfill remediation are urgent incumbents, and robot technology is effective means to supply safe and worthy solutions, on condition to figure out reliable task-oriented architectures and to enable remote-steered duty cycles by implementing the appropriate software-hardware information aids. The paper presents a noteworthy example achievement, specially addressing the requirement analysis, as basic step to develop the instrumental architecture for the measurement and actuation equipment, and to develop the suited remote sensing and control environment, based on an innovative client-server lay-out. The approach introduces actual design demands by explanatory instances, to show how the approach is exploited for the case achievement.**

***Index Terms*— Remote sensing and control, robot drilling, environment pollution, micro-tunneling**

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I. INTRODUCTION

A survey of European Topic Centre on Waste, based on data of six European member states, shows in 13500 European landfills, danger of leachate contamination for subsoil and waterbed. The European Commission in the Directive 97/C 76/01, requests the member states to take the necessary measures to ensure, to the fullest practicable extent, that old landfills and polluting sites are properly rehabilitated. The Microdrainage project gives a reliable solution to reclaim European landfills; using the micro-tunnelling technology, a robot drilling unit creates collecting lines under the landfill that drains away every polluting pools. Due to high dangerous work conditions, the human presence in the tunnel is absolutely not allowed; the drilling robot needs be fully controlled and monitored by operator on the surface (over 300 meters away). These functional constraints, [1], lead to address highly sophisticated set-ups, not available on the market. Thus, the prospected solution aims at developing a purposely conceived robotic equipment, Fig. 1, whose characterising features [2], [3], resort in using a multiple-function boring/drilling head, with automatic rod feeding, done by a manipulation arm from a local buffer. The unit needs track the requested locations along the micro-tunnel and possess two degrees of freedom about a revolving axis, to reach the angular attitude for the expected drilling operation.

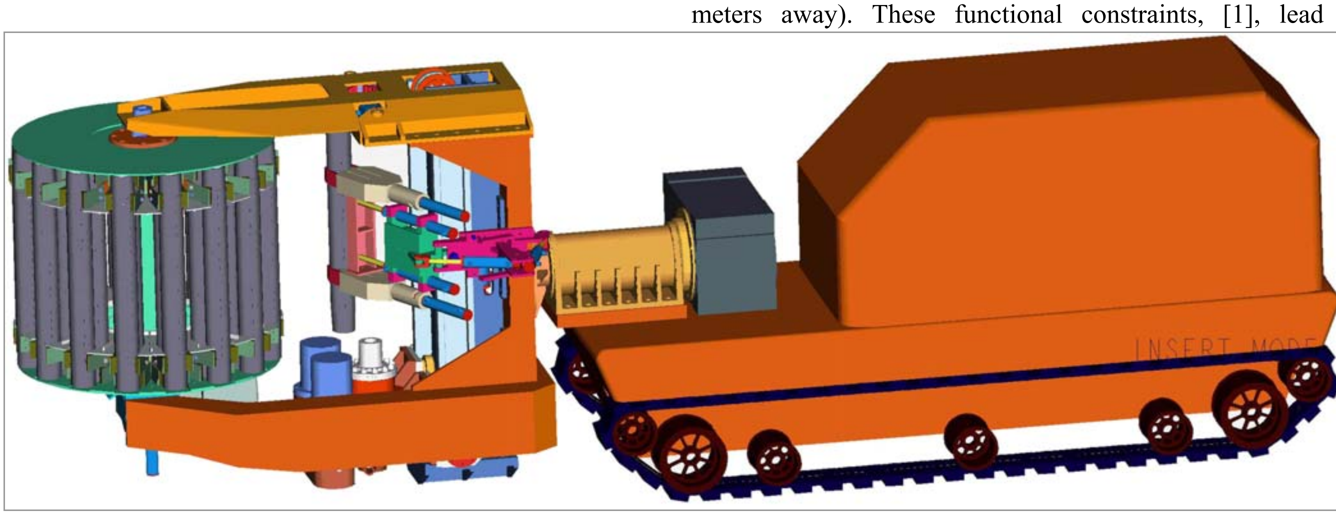

Fig. 1. Main operation elements of the prototypal robotic equipment.

The development of the structural architecture of the robotic equipment exploites digital mock-ups to verify the achievement of the performance objectives and to accomplish the requirement analysis among competing alternatives, [4], [5]. The work eventually issued to a candidate prototypal setting, with accurate definition of the main functional constraints and operation schedules. This made effective turning design and development incumbents, from the configuration and structural, to the monitoring and control requirement analysis and their instrumental implementation. In the following, the characterising features of these challenging issues are summarised, with introductory survey of the innovative lay-out prospected to enable remote operation agendas. All the developments are undertaken within the EU Project MICRODRAINAGE, contract n° EVK4-CT-2002-30012, leaded by the company ICOP SpA of Udine, Italy, specialised in micro-tunnelling, and with the factual support of the firm Tecnigest Srl of Piacenza, Italy, owner of the patented SIDRA® elements, used for the drain piping lay-out.

II. Monitoring Lay-Out And Control Logic

A. Overview

The drilling robot requires three degrees-of-freedom, namely:

- translation along the micro-tunnel, accomplished by the carrying tracked vehicle;
- rotation of the boring/drilling unit, to the angular setting where the draining train shall be laid-down;
- forward push of the pipes train in radial direction, once pierced the reinforced concrete wall.

The remote govern starts with allotting the operation procedures, then, for each procedure, normal working condition and emergency states are specified. The operation procedures are organised at different functional levels. The high level gathers general operations: drilling module moves to target tunnel position, sets up for the drilling operations, imposes the buffer refill position. At the middle level operation, the operator chooses between seven drill duty cycles: to firmly hold the robot at the drilling position; to fetch the special effector and bore the tunnel wall; to plug and drill with first rod, then, to repeat the series of landfill drillings, leaving out the rods; to plug, drill and leave out the last rod; to fetch the special fixture to level out the last rod. The third level is hidden to the operator and is used for debugging or in some emergency state; this level collects the individual action that should be done to complete a second level duty cycle.

In order to assess what is happening under the landfill and how the drilling module is operating, the basic environmental, mechanical and hydraulic quantities are measured, and the most noticeable ones are reported to the operator. Moreover, to offer a synthetic overview, two onboard cameras show the robot positioning along the tunnel, the drilling operation progression and the rod manipulation current state. As general rule, communication black out is main risk of remote control and monitoring; even temporary or lagged defaults, in operator and drilling module communication, could make unsafe the operation progress. To overcome the hindrance, the instrumentation architecture includes on-board intelligence: during blind phases, distributed functions manage the local automatisms and emergencies; moreover, during steady running, they filter and shape the collected data, to assure restitution leanness.

The overview of the actually selected monitoring lay-out and control logic, usefully, splits to deal with:

- the reference positions and the emergency states, considered to characterise the task progression;
- the duty cycles and the operation sequences, specified to describe the standard running conditions.

The two series of information are shortly addressed in the following.

B. Reference positions and emergency states

The development of the governing frame, [6], is based on the accurate acknowledgement of the duty cycles and operation sequences, in order to establish the instrumentation requirements, [7], and the command suites, [8], which enable remote operation prosecution. This functional requirement analysis can be undertaken by different approaches; proper effectiveness is achieved by, first, giving the set of reference positions, which represent the behavioural standards of the robotic drilling equipment, so that the running anomalies are easily classified as emergency states, with proper safety level. According to the chosen approach, one distinguishes:

- drilling robot positions:
  - previously chosen set of locations along the micro-tunnel, where the draining pipes shall be placed;
  - boring/drilling location firming up, by hydraulic jacks, after levelling and attitude trimming;
- drilling head positions:
  - standby position, when “out-of-duty” (e.g., robot moves along the tunnel, buffer refills, etc.);
  - duty position, when the mast is turned to the angular slope of a new duty boring/drilling cycle;
- rod buffer positions:
  - pick-and-place position, generic angular location, where a standard rod is withdrawn or stocked;
  - boring effector position, special angular location assigned to the concrete wall boring tool;
  - first rod position, special angular location from where a drilling rod is taken for a new landfill drain;
  - last rod position, special angular location for a rod with a sealing collar, for ending the drain train;

When in standby position, the head lies horizontal, with the arm on the bottom; its parts bear the following state: all pistons of arm and grippers are contracted; the head drive has the low-speed gear inserted; the vices are open; the unscrewer is disengaged; the mast and head are at zero location; the buffer is at the zero angular location; the holding jacks are retracted. When the head is in the duty position, we shall refer to the standby positions of the different parts, namely: • arm, all rams are retracted; • mast, head shrunk back and low-speed gear engaged; • buffer, boring effector in the zero angular position. Each duty cycle uses these reference positions.

An auxiliary position is allotted to the levelling rod: this is handled by the same arm by a pick-and-place job with modified strokes.

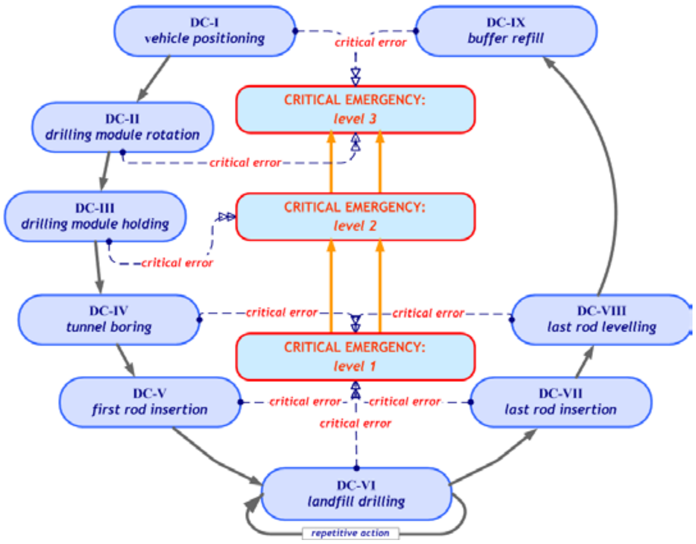

Fig. 2. The emergency flow-chart for the duty cycles management.

The initial requirement analysis identifies the emergency states, with allocated priority at three critical levels, Fig. 2, and a (lower) stop emergency. On the man-machine interface, the on-process diagnostics displays the corresponding alarms, with proper coding and suggested restoring action. Details summarises as it follows:

- high level emergency - work state: the mast is engaged in standard drilling duty cycles and process sensors switch to “failure state” or communication breaks off.
  - *emergency actions*: all parts stop moving; the on-progress rod is cut at the tunnel inner face; the holding jacks fully withdraw; the refill dispatcher (if inside) comes out of the tunnel.
- mid level emergency - work state: the robot holds in the tunnel with firming up jacks enabled and process sensors switch to “failure state” or communication breaks off.
  - *emergency actions*: all parts stop moving; the on-progress rod is cut at the tunnel inner face; the holding jacks fully withdraw; the refill dispatcher (if inside) comes out of the tunnel; the drilling robot is moved out of the tunnel by a tow rope (or equivalent fetching means).
- low level emergency - work state: the drilling robot is tracked along the tunnel, or fixed to the dispatcher for rod refilling, or the head is rotating to required angular attitude, and communication breaks off.
  - *emergency actions*: all parts stop moving; the refill dispatcher (if inside) comes out of the tunnel; the drilling robot is moved out of the tunnel by a tow rope (or equivalent fetching means).
- stop emergency - work state: any.
  - *emergency actions*: all parts stop moving; the on-going duty sequences abort and reset; the drilling robot control switches to manual operation mode.

A local hydraulic accumulator provides the power for the decentralised emergency actions. In addition, the on-progress monitoring reports to the operator, by pertinent warnings, when the standard operations fail. The alarms cover the main criticalities, for instance:

- during robot motion along the tunnel:
  - wrong attitude alarm, when roll (pitch) angle moves out of tolerated figures; *fixing action*: the rubber-sole feeding pump automatically modifies the flow to balance the level plane;
  - high-wobble alarm, when robot vibrations exceed given thresholds; *fixing action*: the advancement speed is automatically lowered (and the operator shall turn to the camera displays);
- or during rod manipulation, from the buffer, to the mast:
  - rod missing alarm, when, at the planned rams extension, the grippers switches do not commute; this might be happen: (a) due to local rod absence, as the refilling operation was not complete or the buffer did not turn correctly; *fixing action*: the arm rams move back to the standby, and the operator is required to check the actual state, before deciding the following task; (b) due to task mismatches, as the camera shows that the rod is actually present; *fixing action*: the operator iterates the task, trying again to catch the rod, or decides to move the next buffer location;
  - one-switch alarm, when, at the planned rams extension, only one switch does not commute; this shows that the rod is not correctly grasped; *fixing action*: the operator iterates the task, trying again to catch the rod, or decides to move the next buffer location;

As general rule, the remote overseeing enables the operator to resume direct control on the task sequences, overriding the autonomous prosecution of the duty cycles.

C. Duty cycles and operation sequences

The standard running conditions characterise by the possibility of applying the *autonomous mode*, assuring prosecution to the end, of the addressed duty cycles. Command programming, thereafter, has three options:

- **autonomous mode**, the robot is switched to perform the scheduled set of duty cycles;
- **quasi automatic mode**, the robot is switched to perform the selected duty cycle or given set of actions;
- **remote mode**, the operator consent is required at the end of each action, before enabling the next one.

A duty cycle generally decomposes into sequences of actions; these could be grouped into tasks or iterated to fulfil the whole requirement. Basically, the two tasks *rod loading* and *rod unloading* are repeated by several duty cycles; these are beforehand recalled, distinguishing *picking*, Fig. 3, *placing*, Fig. 4, and *go to standby position*, Fig. 5, tasks; the differences related to the *special* rods are properly pointed out.

- *rod loading*: the task is continuously iterated during the drilling operations. Special rods, acknowledged at the initial check (and specified by the programmed duties), request appropriate actions:

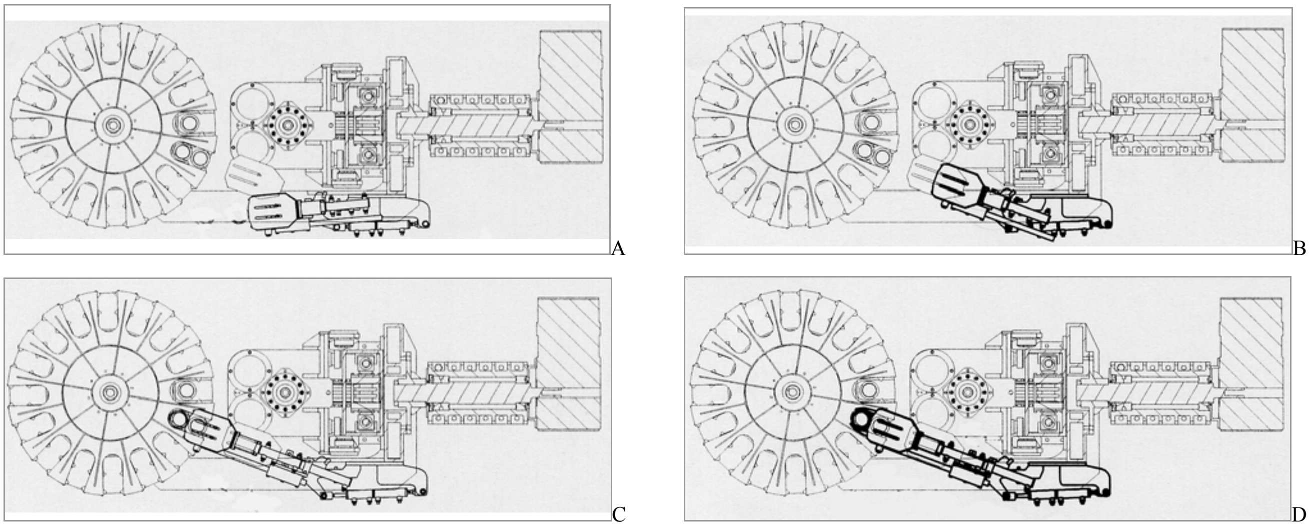

Fig. 3. The action sequence of the arm for the picking task

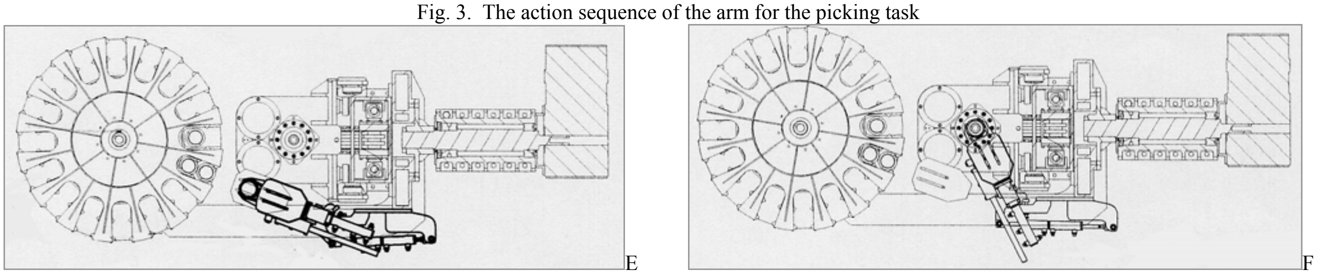

Fig. 4. The action sequence of the arm for the placing task

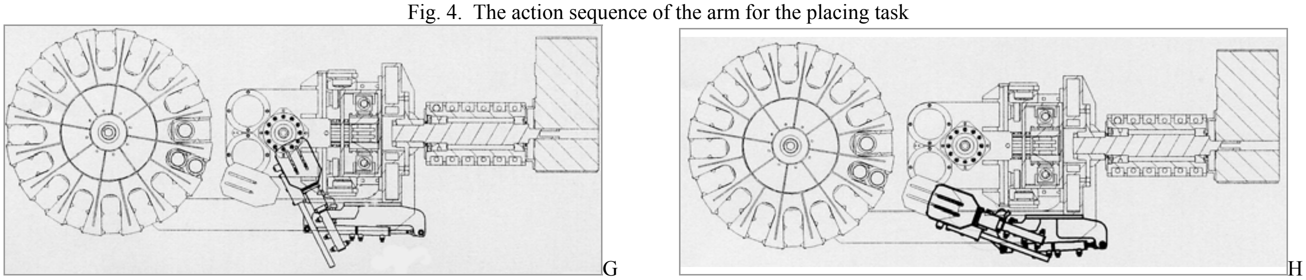

Fig. 5. The action sequence of the arm for the go to standby position task

• the *boring* and *drilling tools* need the unscrewer rig to be fastened on the head;

• the *levelling rod* is located out of the buffer, and the fetch action shall skip to that location;

Besides this, rod loading involves: buffer, arm, grippers, unscrewer (for *boring* and *drilling tools* only) and mast; the action sequence basically develops to accomplish the *pick-and-place* task, Fig. 3:

• *buffer positioning*, the buffer rotates to reach the required angular position, given by an absolute encoder;

• *buffer picking*, outer- and inner-row bars are subsequently addressed; the twin arms have limit switches to specify the reach, the grippers have contact switches to grant the grasp; a camera observes the action;

• *rod positioning*, the arm places the rod on the mast, and keeps it for the un-latching actions, Fig. 4;

• *rod fastening*, the rod is screwed and fastened to the head, then the arm goes back to its standby position.

These sequences, actually, split into elemental actions, with twofold checks: on hydraulic rams (pressure delivery); on mechanical parts (buffer, arm, mast).

- *rod unloading*: the task is accomplished only for the *boring tool* and for the *levelling rod*, as the other rods are left in the landfill, the create the drain piping. The *levelling rod* does not engage the rotating buffer, and require backward *pick-and-place* sequence to the properly assigned nearby position. Summing up:

• *rod unscrewing*, the unscrewer tights the rod and the head unscrews it, once the arm is moved on the mast to catch and hold the rod; intermediate actions are scheduled, to provide proper operation reliability;

• *rod replacing*, the arm moves back the rod to the allotted position (in the buffer, either, nearby it), along the backward FEDCBA path, already shown by Fig. 4 and Fig. 3.

- *arm standby location return*: the task, Fig. 5, is enabled before every *boring* or *drilling* operation.

The recalled approach is followed to divide the robot operations into nine duty cycles, Fig. 6:

■ **DC I**, the robot moves longitudinally along the micro-tunnel, to reach the planned location;

■ **DC II**, the robot rotate the mast, to orient the head along the required radial direction;

■ **DC III**, the robot is levelled and firmly fastened, to accomplish the planned drilling operation;

- **DC IV**, the boring tool is handled, and the micro-tunnel reinforced concrete wall is perforated, FIG. 7;
- **DC V**, the drilling tool is loaded, and the lay-down of the drain piping is started;
- **DC VI**, the rod series is loaded, and the landfill drilling carried on, leaving out the rods, FIG. 8;
- **DC VII**, the last rod is loaded, and the drain piping is fulfilled, with proper bottom sealing;
- **DC VIII**, the levelling rod is handled, and the drain piping is pushed, to not jut out of the wall;
- **DC IX**, the robot keeps the standby position, and the buffer refilling is accomplished.

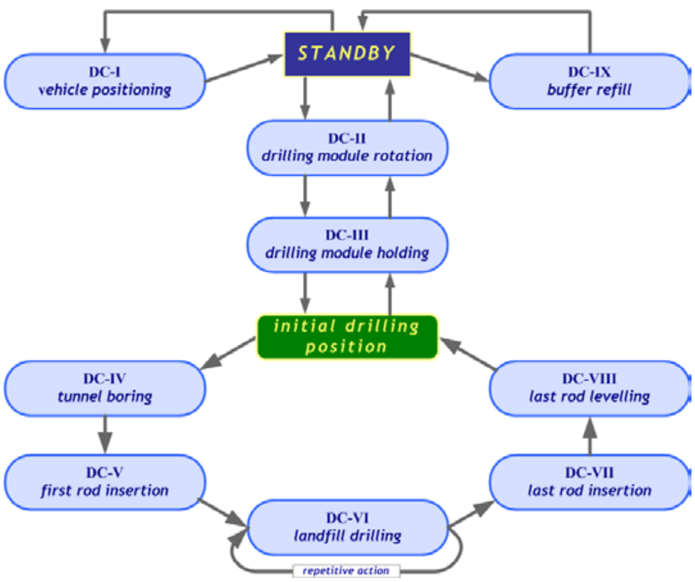

Fig. 6. The duty cycle flow-chart.

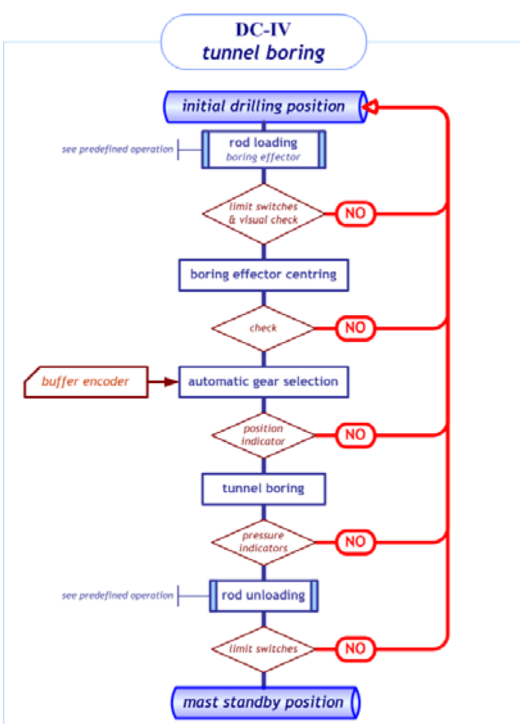

Fig. 7 The wall boring flow-chart

The nine duty cycles can be gathered into three blocks: robot positioning; robot levelling and boring/drilling; buffer refilling. The *autonomous mode* is mostly enabled for the intermediate block, notably for **DC VI**, say, for **DC IV**, **DC V**, **DC VII**, and **DC VIII**; alternatively these are done by *quasi automatic mode*, as well as **DC II** and **DC III**. The *remote mode* is addressed when task progression requests careful concern. The analysis needs go to the pertinent aspects, each time laying detailed operation flow charts. For **DC IV**, for instance, focus turns on the pertinent series of checks, Fig. 7, timely considering the loading of the special tool, its centring on the mast, the automatic insertion of the high-speed gear, the opening execution, the tool unloading and placing back in the revolving buffer. The subsequent **DC V** starts the landfill drilling, and is similar to the subsequent duties, as the rod is left, after proper unscrewing; at the duty end, the arm recovers its standby position. For **DC VI**, the loops iterate, Fig. 8. Once acknowledged the rod loading, drilling thrust and torque are set, acting on pumps pressure and delivery; then head speed and pipe train advance are monitored, up to the threshold. The rod unscrewing is done, using the vice lock and applying head backward rotation, before vice opening. **DC VI** ends, by moving the head to the standby position. The actual reach of the draining duct continuously appears on the monitor.

III. CONCLUDING COMMENTS

The sample presentation of the requirements analysis and duty cycles assessment provides explanatory views of the project. On these premises, the development of the information setting of the operation schedules was turned into appropriate software and hardware aids, [9], and implemented

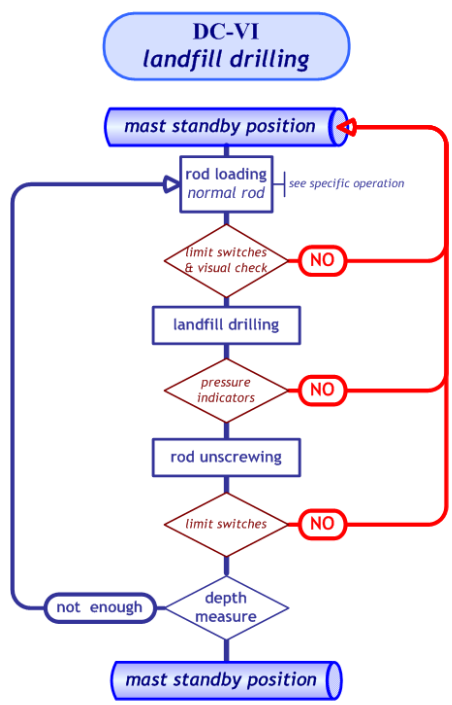

Fig. 8 The landfill drilling flow-chart

to accomplish remote sensing and control, by means of a client-server architecture, having resort to autonomic communication and distributed diagnosis options. The virtual-instrument and mixed-reality lay-out supports were used, to compress the time from ideation to actual construction, starting the on-duty behavioural checks on properly fitted digital mock-ups, in order to complete the joint research programme MICRODRAINAGE, within the EU contract n° EVK4-CT-2002-30012. We grateful acknowledge all the project partners, for their factual commitment and valuable provision with domain expertise and competency in the drilling and draining technologies..

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