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The Virtual Drilling Crew

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***Abstract* – Submarine geotechnical exploration is a challenging task that is currently undergoing a paradigm change thanks to robotics and teleoperation. The MD500 Project is an underwater subsea geotechnical drilling and in situ testing device designed to sample and probe up to 150 m of soils of rock beneath the seabed in water depths of up to 500 m. The system has applications in several areas of marine activity, such as port infrastructure, nearshore and offshore renewable energy projects, oil & gas, submarine mining, etc. The machine consists of a group of devices operated remotely and that must synchronize with each other: drilling tower, stabilizing legs and three manipulators (two cartesian and one anthropomorphic). These manipulators can be operated manually or in a semi-automated (robot) mode. The automated routines aim to substitute the actions of the drilling crew when handling the tubes and rods in the harsh environment for which the machine is envisioned The paper presents an overview of the code and logic behind the tool manipulation and handling routines of the MD500, which are at the core of a "Virtual Drilling Crew" inbuilt in the machine design.**

I. INTRODUCTION

The most important consideration when planning an offshore geotechnical campaign is the high cost of equipment deployment. In shallow waters, geotechnical surveys are usually carried out from jack-up platforms directly supported at the bottom. For depths beyond 30 m the size and cost of the jack-up platforms needed to reach the bottom and withstand environmental actions, while offering adequate shelter to the operation crew, increases very significantly.

The obvious alternative is to use vessels. The size, type and cost of the vessel needed depends on the depth and methods used for sample retrieval. The main two methods are:

1. From drilling vessel (downhole method – according to ISO19901-8 nomenclature [1]), in which the testing and sampling are carried out from a ship through an assembly of drill pipes.
2. Using remotely operated underwater machines (seabed mode – according to ISO19901-8 nomenclature [1]), in which the rig, is placed on the seabed and operated remotely.

In the downhole mode, a specially designed geotechnical drilling vessel that includes a drilling rig and a number of ancillary systems (heave compensation, suitably sized moonpool) is necessary. These ships are relatively big – 70 m lengths are common- and scarce. The machines in the second option usually have a size small enough to be stored in standard 6 m containers and their weight ranges from 10 to 15 tons. Medium size vessels, designed for geophysical research of offshore platform supply are generally sufficient to deploy these pieces of equipment, thus reducing the cost of the campaign. However, the main drawback of this approach is the availability of these machines, since there are only a few operational worldwide. This limited availability was the main motivation behind the development of the MD500 Project; the next pages are a synthetized overview of the control software and architecture that make possible to replace a drilling crew with a set of underwater robots and machines.

II. SYSTEM'S GENERAL DESCRIPTION

The machine (depicted in Figure 1) consists of several modules: drilling rig (1), robot arm manipulator (2), Cartesian robots (3), stabilizing legs (4), sample tubes storage (5), rods storage (6), electric and hydraulic power and communications unit (7), drilling mud system (8) and wireline system tools (9).

All these elements must synchronize their individual tasks in order to achieve the main goal: retrieving soil samples without introducing further alterations or disturbances besides those inherent to the drilling process. Each cartesian robot has the task of managing and handling either the sample tubes or the drilling rods. The robot arm must handle the elements fed by the other two robots and place/remove them accurately in the drilling rig while synchronizing with multiple grippers that make possible to assemble/disassemble multiple rods, and also with the wireline winch to retrieve the sample tubes so they can be stored once again.

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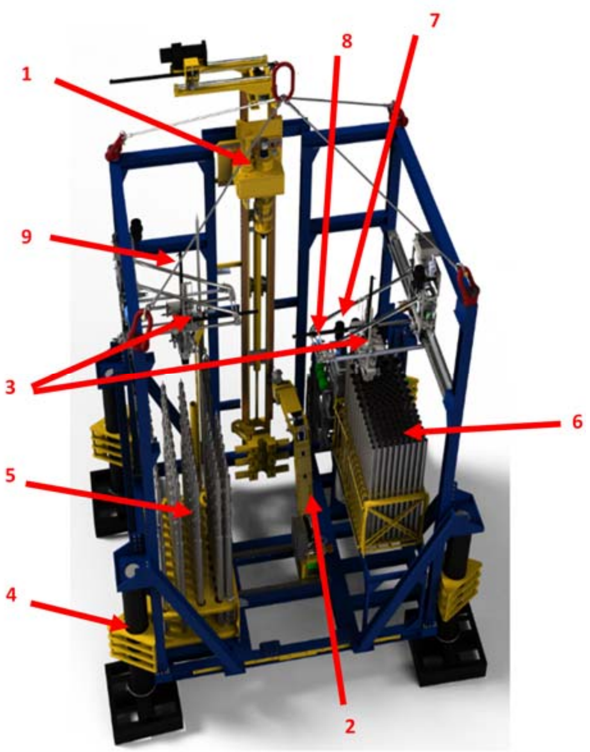

Fig. 1. 3D render of the machine.

III. CONTROL ALGORITHMS

The machine is operated remotely from a graphical user interface (GUI) in the master PC. From this application, the operator can select automated routines or manual commands to be executed by the devices. These instructions are sent via Ethernet to the communications unit, where they are translated to CANbus messages and interpreted by one of the six Bosch Rexroth BODAS RC PLC's, one for each of the building blocks of the machine (robot arm, cartesian robots, legs, drilling rig and drilling mud system).

The general architecture of the control program "template" for the PLC's is shown in the Figure 2. The servo thread (Figure 2a) has a higher priority in execution time (needed for the control loops) while the default thread (Figure 2b) handles low priority processes and the communications with the master PC. The general logic behind the automated routines and manual commands selection and execution is shown in Figure 3.

Semi-automatic routines are envisioned for reducing the work load and stress of the operator. Repetitive tasks such as picking up and storing tubes and rods, placing and removing elements from the drilling tower and homing procedures are examples of the multiple repetitive tasks programmed in the PLC's. There is a verification pause at the end of each step of the routines, a "Continue" instruction must be sent in order to resume the routine.

Nonetheless, manual commands can be sent during programmed pauses. The manual commands are useful for correcting (if necessary) the end position at the end of each step of an automated task. However, they are also useful if an incident occurs, for instance a tube falls, then the operator can decide if the tube is in a reachable position (according to the visual feedback of cameras) for the arm and try to retrieve it. Another scenario could be the small displacement of sample tubes in the storage area due to landing or machine handling procedures; then, similarly, the final position of the cartesian robot can be adjusted accordingly.

A. Path Generation and PID Loops

Linear function with parabolic blends [2] is the interpolation method chosen for creating point-to-point trajectories in cartesian space. In other words, linear acceleration/deceleration ramp motion profiles. To create a smooth path with continuous position and velocity a linear function is used initially and then a "blend" region is added at the end of each point. In the linear portion of movement each axis coordinate position, velocity and acceleration are:

$$x = x_j + \dot{x}_{jk} t, \quad \dot{x} = \dot{x}_{jk}, \quad \ddot{x} = 0 \tag{1}$$

Where x_k is the finish position, x_j is the start position, $\dot{x}_{jk}$ is the max velocity for the movement and $t$is the total duration of the movement, calculated at run time. In the blend portion of the movement these variables become:

$$x = x_j + \dot{x}_{jk}(t - 2t_b), \quad \dot{x} = \ddot{x}_k t_b, \quad \ddot{x} = \ddot{x}_k \tag{2}$$

Now t_b represents the duration of a blend segment, also determined at run time, and $\ddot{x}_k$ the desired acceleration. The first blend segment lasts until the max velocity is reached, then the duration is stored as the starting point of the deceleration phase. A path generation instance produces, at run time, the setpoint positions (trajectories) that the control algorithm should track. The variables to control are angular and linear positions measured via incremental encoders and the actuators are proportional hydraulic valves.

A detailed model of the hydraulic systems (cylinders and motors) [3] would be ideal for designing the control law but to practically impossible to formulate because of the impossibility of estimating highly varying disturbances and nonlinearities, like the friction in the joints bearings (especially in the robot arm), or the change of oil viscosity with temperature which modifies largely the effective flow rate. A robust control law that does not depend on the

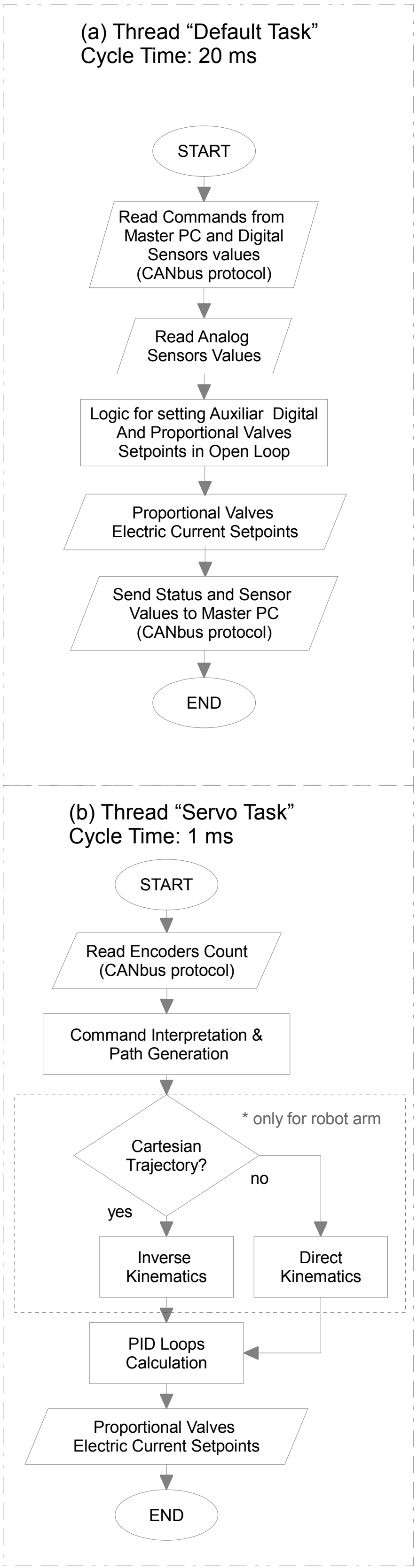

Fig. 2. Main threads flowcharts.

system's model was needed and in which the tuning can be carried out empirically with the aid of experienced hydraulics technicians: the ubiquitous PID controller. The discrete time version of the well-known control law is described in the difference equation:

$$u(k) = K_P e(k) + K_I \sum_{i=0}^{k-1} e(i) + K_D[e(k) - e(k-1)] \quad (3)$$

For implementing a position control loop: u is the electric current applied to the proportional valve; e is the position difference between the feedback and the set point measured in incremental encoder pulses and K_P, K_I, K_D are the proportional, integral and derivative gains; k represents the current time cycle and $(k-1)$ the previous one. Equation (3) can be easily translated into code ([4], [3]) that is executed within each servo cycle. Minor changes are made to the basic PID algorithm for taking into account some nonlinearities such as the saturation of actuators and the implementation of a sign function for changing the direction of movement – both features of 3/2 proportional valves controlling differential hydraulic cylinders.

Actual implementation of this position control loop requires fine tuning of the PID gains and the gear ratios for encoders and gearboxes, as well as areas ratios in hydraulic cylinders. An instance of this algorithm is needed for each axis to control. An empirical approach for tuning the gains has been used so far, further work will include an implementation of a more sophisticated algorithm like the one proposed in [4].

The robot arm's objective is to execute a variety of tasks with different levels of complexity, from picking up and placing sampling tubes and rods, to turn valve handles in order to reduce the already high number of actuators placed through all the machine. The robot arm must be versatile enough to replace the crew carrying, placing and assembling tubes and rods. To do so, the routines and manual modes of operation are an augmented version of the "basic control template" (Fig. 3).

Cartesian, cylindrical and joint modes are available for manual commands. The first one uses the inverse kinematic model, the third the direct kinematic model and the second needs both models. The inverse kinematic model yields the angular positions that joints must adopt for a given set of coordinates of the end effector (in this case, the robot's gripper), whereas the direct model does the opposite. Examples of both model of a 5 DOF anthropomorphic arm are presented in [2], [5] and [6].

IV. HUMAN MACHINE INTERFACE & SUPERVISORY CONTROL & DATA ACQUISITION (HMI & SCADA)

After reception of every message sent from the PLC's, a thread is launched in the PC master main application, in order to classify, decode, process and access the operations

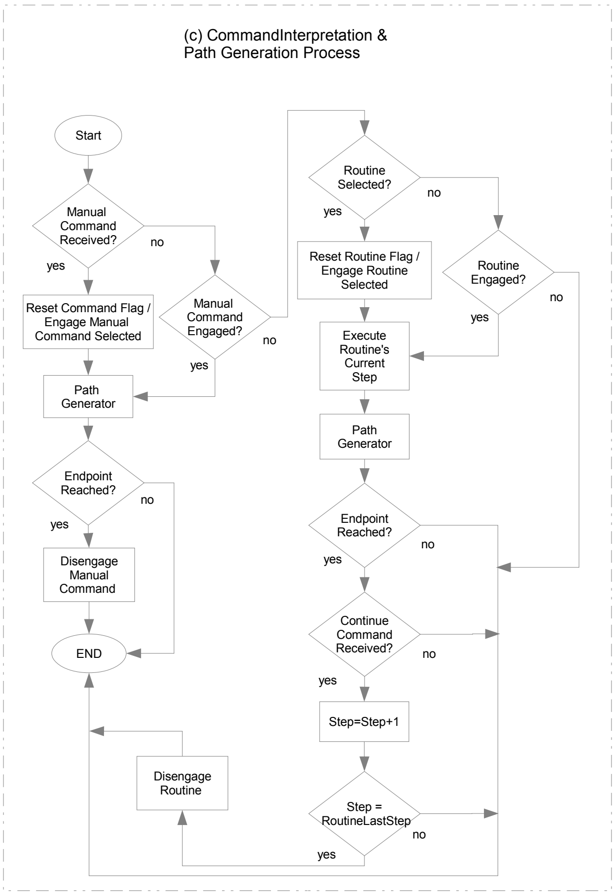

Fig. 3. Command interpretation function flowchart.

database as a set of parallel processes. Data immediately relevant for the operations is stored in a temporal database and displayed in form of charts, 3D animation –working as a sort of augmented reality system (Figure 4) -, and gauge indicators.Pressure sensors are used for visualizing the drilling head torque, the tower downward force, temperature sensors are used to monitor the oil and motors status, incremental encoders register the position and velocity of the drilling tower (and for each robot axis) and the rotational speed of the drilling head. Also, an inertial measurement unit (IMU) is used to know the orientation when landing and drilling and in combination with the 3D display is a helpful feedback for operating the stabilizing legs.

Real time charts of relevant drilling variables (according to ISO/DIS 22476-15 guidelines [7]) and cameras seek to replace the technician "sight and hearing", giving him all the information needed to drill under different soil and environmental conditions. By logging and building a historic database, posterior analysis of the operator's decisions is possible. The aim is to eventually build an expert system taking into account the expertise these professionals have gained in the field during many years and further automate the machine.

Fig. 4. Human Machine Interface screen sample.

V. ACKNOWLEDGEMENT

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