APPLICATION OF ELECTROHYDRAULIC CONTROL SYSTEMS WITH EARTH MOVING MACHINERY

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ABSTRACTS

The complexity of the construction machine with its working implements has reached a degree at which the driver is no longer in a position to operate the machine continuously in the most efficient way. By introducing closed control circuits the operator can partly, or in some cases entirely, be relieved from the execution of certain functions of the machine.Necessarily this target can only be achieved by the application of microelectronics in connection with variable hydraulic systems. Especially the problems of the sensor systems and the requirements of the electronics under the severe operating conditions of the construction machine have to be met. By means of examples already installed, systems of this kind are presented and their function are discussed and evaluated also with respect to the efficiency of their application.

1. INTRODUCTION

By means of the examples described, the present possibilities but also the still existing limits of automation are demonstrated. We can assume that the fully automated construction machine should be a goal for the far future but that this can only be realized step by step. In the partly automated construction machines of today, these functional modules are frequently all separately arranged as a kind of "isolated solution" and are, therefore, without interaction. This would be a must, however, if the above mentioned aim - namely the fully automated construction machine - has to be achieved.

A precondition for automation of an operating cycle is, therefore, that it can be mathematically described. Defining such operating cycles is all the easier, the more correct the working result desired can be defined, using the same formulas over a certain period of time, or period of travel, or in the cyclic and repetetive operations where the result is reiterated in the same way. The working result to be achieved can in most cases be shown mathematically. The position of a fine grade, or the degree of compaction of a fill or embankment, e.g., can be expressed in geometric, or physical terms. It is, therefore, quite self-evident that one of the greatest difficulties results from storage and shape of the material to be dug. The material to be mined, shifted or loaded cannot be described at all, or only preliminary. It is almost impossible that the work tools like an excavator, or loader bucket can find the proper starting point itself; therefore, it can likewise not carry out the loading procedure on its own according to a predetermined curve in the system. Additional information on the material position, such as the cutting pressure, must be supplied to the machine.

Less complicated, however, is the control of components in the construction machine, such as engine, transmission, hydraulic motors and pumps. The function of these components can be clearly described mathematically because their operating data, or characteristics are known. This system also incorporates interconnected controls of several components - also now commonly referred to as "power train management".

2. AUTOMATION OF THE POWER TRAIN AND MOVEMENTS OF THE WORKING TOOLS

2.1. PUMP-MANAGING-SYSTEM (PMS) FOR EXCAVATORS

The pump managing system is a system of microprocessors for monitoring and governing the hydraulic pumps and the drive engine. The main component of the PMS is the electronic pump load limit regulation, limiting the power take-up of both working pumps in such a way that the available engine output is not exceeded. The hierarchy of control of this three-pump system is demonstrated in Figure 1.

The regulating variable of which the instant load on the engine is derived, is the change in the engine speed. With increasing load, the engine speed is dropping slightly and with decreasing load the engine speed is increasing. As every change in load is registered by a change in the engine speed, for systems with pump load limit regulation it is not necessary to generally hold a power reserve for additional equipment and for extreme operating conditions.

The pump load limit regulation also automatically knows when one of the pumps is working below the limit because due to the total load being too low the engine speed would rise. In such a case the permissible output of both working pumps is increased which has no influence on the reduced output of the pump working below the limit. For the other pump that is working within the limit, the increased permissible output is leading to an increase in pump delivery. The permissible output of the working pumps is determined by means of the following equation:

$$P_{p.perm} = 0.5\,(P_{M.perm} - P_{Sch} - P_{NV})$$

$P_{p.perm}$ = permissible output for one working pump
$P_{M.perm}$ = permissible engine output
P_{Sch} = output taken up by the variable displacement pump
P_{NV} = output taken up by the auxiliary consumer

The output regulators of the main pumps are hydraulically adjusted over a proportional valve in such a way as to always utilize the entire engine output.

With the three-pump system the operator of the excavator can - the same as with the conventional hydraulic excavator - select the engine speed freely with the throttle control. For operations not requiring the full engine output, it is possible to work with low engine speeds. The noise emission and the fuel consumption are thus reduced.

Besides the electronic pump load limit regulation, the Pump-Managing-System has other functions in monitoring and governing the engine which cannot be put into practice with a hydraulic system. By using the freely programmable microprocessors this is no problem anymore. The PMS is constantly monitoring the cylinder head temperature of the engine. If the temperature rises above a certain limit, the permissible output of the engine is reduced until the temperature has dropped again below that limit. This results in a longer service life of the engine, because the engine cannot be overloaded anymore by an increased ambient temperature or other irregularities - such as a contaminated cooling system. In Figure 2 the temporal splitting up of the engine output over the three pumps as well as the engine output used for the operating cycle is schematically illustrated. For this purpose, the upper carriage is slewed by 90° for loading a truck.

As an option, the engine speed lowering during breaks can also be governed by the PMS. If there is no output required for more than 10 seconds, the engine speed automatically drops down to idle speed. At the same time, the output regulator of both main pumps is set on minimum. When operations must be carried out at low speeds but with the digging and break-out forces remaining the same, the operator can select a lower power stage. This system is referred to as Power Control. The power control results in a reduction of the permissible output of both working pumps - which is calculated by the electronic pump load limit regulation - to 75 % or 50 % and the output regulators of the main pumps are accordingly set lower.

The decisive advantage of the Pump-Managing-System is that the regulating and monitoring functions can be changed or extended almost to no end by programming the microprocessors as required. Future further developments can be integrated in the system without any difficulties.

2.2. COMPUTER-ASSISTED LOADING (CAL) OF LARGE EXCAVATORS

Digging, that is to say filling the bucket and emptying, which means loading the transport vehicle,are the power-determining phases of the operating cycle. These operating cycles require enormous skills and full concentration of the operator.

Lifting the filled bucket to the dumping point, or placing the empty bucket into its digging position are routine jobs compared to this. Lifting, dumping and slewing the upper carriage must overlap so that the bucket has to cover only a short distance at optimum speed.

These bucket movements are almost the same from operating cycle to operating cycle. For this reason, it is purposeful to let these cycles run automatically - computerized (Figure 3). The job of Computer Assisted Loading (CAL) in hydraulic excavators basically consists of two parts, namely:

- Teaching and storing a movement
- Execution and travelling that movement

Such storing of a movement, due to the many different operations of an excavator, is only possible with the teach-in method. This means that certain phases of a certain operating cycle are initially carried out by the operator and at the same time taught into and stored by the computer.

The "Teach-in"-programming starts at the dumping point of the empty bucket over the dumper. For this, the "start" button at the operating lever must be pressed. The operator now positions the bucket to the digging point of the pile. In doing so, the function "lower boom" is defined as point of "articulation". This point is at the same time the point of collision with the dumper. Once the digging point has been reached and the bucket is placed in excavating position, the operator has to actuate the "target"-button. Start, collision and target point are then stored.

After "teaching in", the automatic operating mode can be started by pressing the "automatic"-button once. Depending on the previous activities, the loading, or the dumping point is steered at taking the point of collision into consideration.

The computer is in a position to optimize the stored movements. This means:

- optimum bucket movement during lifting and lowering as well as
- the taught-in movements at highest possible speed.

During automatic travel, the operator can interfere at any time and take over control of the excavator himself.

The CAL-system can be extended considerably by connecting what is referred to as optional computers. The data exchange of the individual option modules is done via a data bus. For example, the weight of the bucket content can be measured, among other things. For this purpose, the weight computer is fed with the individual position of the tool as well as the cylinder pressures and the angle of inclination of the base machine. The loading performance per hour, or per day can also be calculated.

For underwater excavating during which the operator cannot see the position of the boom and the bucket, it is necessary that their position is shown on a monitor. This is done over a monitor module which is processing the measured data of the already existing sensors.

2.3. COMPUTER-ASSISTING-PROFILING (CAP) FOR EXCAVATORS

For many operations performed by the excavator not high loading performance but utmost accuracy is required. For example:

- for a rough grade
- for an embankment
- for a profile ditch
- for a base in sewer construction

For operations as mentioned above, frequently small excavators are used.

For these operations, the "teach-in" of operating cycles is also suitable. The movements that are important for the operation are carried out first by the operator and stored in the computer. During automatic travel the curve is "taught-in" before it is optimized by the computer, i.e.

- the digging curve of the bucket is smoothened,
- the movements are carried out more fluently and almost without any transition.

The operator, however, has also the possibility to preselect a certain angle of embankment on the keyboard of the display installed in the cab. The cutting edge is then travelling along the gradient of the slope surface on its own. The advantages of the CAP systems can only be fully used, however, if the computer is connected to a rotating laser. (Figure 4). The transmitter of the laser - system is positioned in the field marking from there an artificial horizon, which is independent of the excavator's position.

The receiver of the laser is attached to the bucket arm of the excavator. The receiver is connected to the computer and whenever passing through the artificial horizon, the present position of the boom geometry is fed into the computer; the present position is then compared with the "taught-in" position and, if necessary, newly programmed.

2.4. AUTOMATIC MOLDBOARD CONTROL FOR GRADERS

The requirements on the flatness and tolerances of the level of the fine graded surface on road - airport - and sport sites construction have been constantly increased in the course of the years. Therefore, meeting these requirements frequently exceeds the operator's abilities. The level has to be measured repeatedly in order to attain the prescribed values. These tasks can be effected much more rapidly and more accurately, too, by means of an automatic moldboard control. Operation of the grader can in this case be confined to setting the prescribed position values concerning the level, steering the machine and monitoring the material flow. The entire system of the moldboard control is a modular kit which can be assembled from its basic elements to suit the construction job carried out in each case (Figure 5):

- Control of the cross inclination (slope) of the moldboard
- Control of the cross inclination and the height of the moldboard either by means of a reference wire line, or by means of a given level
- Angle compensation
- Moldboard control by laser.

The fundamental principle of this system is based on the cross inclination being controlled by a pendulum always showing the vertical line. The height sensor mounted to one end of the moldboard, controls the height. Hereby, either a tracer rod scans a reference wire strung along the side of the grade to be made, or a tracer wheel runs along an already fine graded track. The latest development in this field is the "touchless" scanning of the height by means of an ultrasonic feeler; the reflexion time of the waves sent out is the measure for the distance to the ground, or any other reference line. As the sound velocity in the air depends on the temperature, a temperature compensation must be integrated to ensure achievement of the necessary accuracy for regulating the height.

The angle compensation serves to avoid the lateral inclination of the grade deviating from the preselected value. As the ideal rotation axis of the moldboard, seen from the side, is not exactly perpendicular to the ground, deviations occur when the moldboard is performing any rotating movements. A longitudinal inclination indicator is measuring the angle between the drawbar and the vehicle frame, serving as reference line that is parallel to the ground; the rotating angle sensor determines the rotating angle of the moldboard. By using these two values, a correction signal is calculated and fed into the control circuit. The driver is, therefore, completely free in setting the moldboard; he merely has to adjust the moldboard so that the material is rolled off in the most favourable manner. The signals coming from the pendulum and from one of the height feelers mentioned are processed by the electronics and transferred to the solenoid valves as output signals; the solenoid valves start moving the hoist cylinders of the moldboard.(Figure 6). The control of the valves is done by means of the pulse width modulation. This kind of control has the advantage that the valves - due to the excess power moving up the spools- are more resistant to contaminations and any drifting in 0-position is not possible because of the closed central position with overlapping .

For fine grading of large level areas of any inclination, the moldboard can be controlled by a laser beam. A rapidly rotating laser beam spreads a light plane by which the receivers, attached to the ends of the moldboard, are controlled. A further advantage of this system is the fact that the grader can move completely free in all directions and shift the material anywhere.

2.5. ANTI-SLIP CONTROL BY RADAR OR SONAR

In order to achieve the maximum shifting performance with wheel-tired planing or loading machines, the maximum tractive effort, which results from the power transmission ratio between tire and ground, must be applied. The driven wheels are always slightly ahead with a certain slip value compared to the ground. Keeping the maximum tractive effort requires utmost concentration and skill of the operator, or to avoid any of the disadvantages mentioned, he will often work below the machine's performance limit.The maximum possible tractive effort will be realized by the speed measured by radar and the thereof calculated slip. This ensures getting top performance of the machine in a widely automized operating process and at the same time the driver's job will be significantly relieved. (Figure 7).

The slip value S is defined as follows: $S = (v_u - v_{ist}) : v_u \cdot 100$ (%) with v_u as peripheral tire speed and v_{ist} as actual vehicle speed "above ground".

The peripheral tire speed is determined as pulse frequency via a sensor on the gear wheel on the output shaft of the transmission to the axle, the peripheral tire speed is proportional to the pulse frequency, taking the number of teeth, the axle transmission and the tire radius into consideration. For determining the actual speed, use is made of a radar. The radar sends out high-frequency electro-magnetic waves that are reflected to the radar velocity sensor by the ground. In the unit itself, the wave length of the waves returned and those sent out is compared and the difference - which is a measure for the speed - is emitted as frequency. As an alternative, it is possible to use transmitters, called sonars, which are working on the basis of ultrasonic waves. With this system, analog to the radar, acoustic waves are emitted.

The two pulse frequencies are now compared in a microprocessor and thereof the slip value is calculated according to the formula mentioned above. If any deviations from the preselected set value occur, an amplified electric signal is emitted to the solenoid valves to reset the moldboard. These valves are likewise controlled according to the principle of the pulse width modulation. Before the system is put into operation, it has to be calibrated by simply letting the machine roll out when the switch is positioned on "calibration". In this situation, the slip value is S = 0 (%) because the wheels roll off without spin versus the ground. This value is stored as initial value in the microprocessor. Therefore, it is not necessary to input any machine-specific values, or reprogram after a tire change.(Figure 8). The operator can set the slip with a turning knob, as the value at which the tires transmit the maximum tractive effort varies, depending on the ground. Soft grounds require a higher slip value than tough grounds for transmitting the maximum tractive effort because the tires penetrate more into the ground there.

3. AUTOMATION OF THE DRIVE UNIT

3.1. FRONT-WHEEL ELECTRONIC DRIVE CONTROL (EDC) FOR GRADERS

The front-wheel drive of the grader encounters difficulties due to the awkward shape of the front frame parts, colloquially referred to as "goose neck". Fitting the mechanical elements such as joint shafts around the "goose neck" is creating enormous technical problems and, as a result,is rather expensive. For this reason, the hydrostatic drive was introduced. The hydrostatic drive, however, has completely different driving characteristics than the rear wheels. The rear wheels are driven by a torque converter combined with a mechanical powershift transmission.

The EDC now ensures that under all operating conditions, the front and rear wheels are synchronized, or that a constant advancement which the driver has preselected according to the requirements on the job is kept .(Figure 9). The commonly used method for synchronizing, to compare the wheel rotational speeds, was deliberately not applied here due to two facts. Firstly, it would necessitate to record the steering angle of the front wheels and secondly, the low rotational speed of the radial piston motors in the hubs of the wheels would deliver only pulses by the magnetic pick-up with very low frequencies.

Therefore, the rear-wheel speed is recorded by sensors as well as the rotation of the diesel engine; from these two speeds, the pump swing angle is calculated which delivers the oil flow required for synchronization. As with reduced driving speed, the efficiency of the wheel motors, as well as the pump is somewhat dropping due to the then also reduced swing angle, their compensation was fed into the calculating program so that almost over the entire speed range exact synchronization is maintained. In addition, the driver can over a mode switch preselect a certain advancement and so determine the aggressivity of the front drive. When driving round bends, the increased oil flow, deriving from the compensation of the efficiency, compensates the difference in in the travel between front and rear wheels so that there will not occur any significant strain. (Figure 10).

The front-wheel drive itself consists of an electrically controlled displacement pump, operating in a closed circuit and the hydraulic wheel hub motors. The signal emitted by the microprocessor is transferred as proportional voltage to the electro-hydraulic displacement organ of the pump.In doing so, the required oil flow for the wheel motors is generated. The pump controller is also equipped with a pressure limitation once the maximum allowable pressure has been reached.

As the front-wheel drive is effective up to speeds of 25 km/h, the displacement of the wheel hub motors is shifted to half in the 4th and 5th gear in order to prevent the oil flow from rising up to values exceeding the maximum output of the pump. By means of an input device, the programs stored can be changed or, if signs of wear are registered after a longer operating period, the corrective factors for the displacement compensation can be adjusted to the somewhat worsened volumetric displacement.

This input device serves at the same time as control and monitoring unit.

3.2. AUTOMATIC TRANSMISSION SHIFT

Partial automation of the driving procedure is achieved by automatic transmission shift. With the automatic gear shift, the gear is always changed at the most favourable point of time. The latter is calculated by the electronic system, considering the crucial operating data such as engine speed, present driving speed, converter slip, engaged gear, position of gas pedal and possibly a brake signal. Systems of this kind can nowadays be found in wheel loaders and dump trucks.

3.2.1. WHEEL LOADERS WITH TORQUE CONVERTER TRANSMISSION

The automatic gear shift facilitates the operator's job significantly. During the loading procedures he has to keep one hand on the steering wheel and the other one on the hydraulic lever. The automatic transmission according to Figure 11 now shifts into that gear which is most suitable for the prevailing operating condition. The driver, in turn, can override the automatic transmission via a kick-down. The automatic transmission also incorporates locks, protecting the engine and the transmission to a great extent. Especially the disadvantageous overspeeding on down grades can no longer occur because the safety function of the transmission is then released. The speed of the engine is reduced by the automatic shifting of the transmission into higher gear.

Nowadays, driving diagrams are set up with the help of computers. The shifting points in the automatic transmission are defined by taking the type of machine, the gear selection of the transmission, the engine and the converter type into consideration. The judging criteria are tractive effort, fuel consumption and shifting quality.

3.2.2. WHEEL LOADER WITH HYDROSTATIC DRIVE

Wheel loaders with hydrostatic drive, able to drive faster than 30 km/h, need an additional mechanical 2 or 3 gear shift transmission. Since claw transmissions that can only be shifted during standstill are nowadays, apart from installations in a few small loaders, not up to the state of the art anymore, the powershift transmission is the system used also here more and more. During shifting, jerks can occur which are caused by the hydrostat's characteristics, or certain operating conditions. The shifting electronics developed to avoid these jerks, guarantee a smooth transition from one gear to the next. The gears are preselected by means of a switch.

The scheme in Figure 12 illustrates that the shifting is performed by the electric influence on the hydraulic pump in dependence of the recorded speeds. The selected shifting strategy prevents the hydropump or motor, as well as the diesel engine from overspeeding , a danger when shifting into lower gears during downhill travel.

3.2.3. DUMPERS

In the case of dumpers, the requirements which have to be met by the automatic transmission are even more complex. First of all, the automatic transmission is to change into that gear which guarantees the most economic engine operating point with respect to fuel consumption in the performance curves of engine torque versus engine speed. A converter lock-up, the shifting points of which are likewise programmed, assures that after the starting procedure has been completed, the transmission continues to operate without any converter losses. The integrated retarder is set in such a way that when driving on down grades the speed is adjusted to the road conditions. Figure 13. The automatic execution of the shifting procedure has, furthermore, the effect that the entire drive line from the engine to the wheels is less subject to wear and that unfavourable gear shifts are avoided. In addition, it is possible to predetermine various shifting programs which are filed in a memory, such as:

- an economic program, aimed at optimizing the fuel-saving operation,
- or a power program for high driving performance on difficult terrain.

At present, driving programs are being developed to suit the individual ground conditions of a certain mining plant, or a construction site.

4. DIAGNOSIS AND MAINTENANCE

4.1. BOARD-CONTROL-SYSTEM (BCS) FOR LARGE EXCAVATORS

The constantly increasing complexity of the systems used in construction machinery requires a large number of receiving, measuring and checking devices (Figure 14), the permanent monitoring of which is asking for much of the operator's attention, if not at all too demanding to him.

Driver information systems offer the possibility to make the driver's job easier. The purpose of this system is not only to display all major operating data in one form so that the driver's job is rendered as easy as possible but that he is also given down to fact operating instructions.

The Board Control System monitors important functions of the excavator and its units. The BCS reports and stores any exceeding of preprogrammed limit values. If the operator has to take any actions, e.g. turn off one of the two diesel engines, he is given the instruction on the screen. The BCS is also giving information on maintenance and trouble shooting. Sensors are installed on different operating points of the excavator, reporting their measured value to the BCS computer. Important operating data are displayed on the screen as indicator instrument. Other operating data, such as operating hours of the excavator, the engines, the drive unit and the swing gear are stored. (Figure 15).

Since the BCS automatically reports any operating conditions which are not normal, or even takes suitable countermeasures, the operator can fully concentrate on his job. His attention is not disturbed by having to observe a number of measuring instruments, or by having to think what measures must be taken, if one or several limit values have been exceeded. The operator and maintenance staff, however, can recall data from the BCS that are not permanently displayed or stored.

4.2. TEST AND INPUT UNITS

For customer acceptance, it is a must that the components installed in electro-hyraulic control and regulating systems do not fail more often, than other machine components which are often more simple in design. As defects in these complex electronic systems mostly cannot be detected from the outside, auxiliaries for trouble shooting must be provided.

The test and input unit as shown in Figure 16 meets the requirements demanded on operation, diagnosis and maintenance in a universal manner. The unit is connected to the machine by means of a plug - a suitable possibility for connection must be guaranteed, of course. The data of the program called with a key button are now shown on a display.

- Time program
- Trouble-shooting program
- Programming program
- Printing program
- Foreign language program
- Calibration (self-adjusting) program

With the trouble shooting program it is possible to trace malfunctions in electric parts, such as sensors, processing electronics, solenoid valves and the like, as well as in the hydraulic part of the system, where mainly oil pressures are being checked. Malfunctions that were detected in the individual menus can be printed out before, or after repair.

Of particular importance is here the programming program which allows certain factors of the program stored in the computer of the system to be changed; as a result the characteristics of these factors are adjusted to certain operating conditions of the construction machine on site and therefore optimum machine performance is achieved by exact adjustment to the requirements.

5. CONCLUSION

Electronics in connection with servohydraulics is generally experiencing thriving development. This development will be of advantage for the industry of construction machinery, too. The market offers elements and components to the construction machinery industry which are in close cooperation with specialized firms already adjusted to the specific requirements. Another main emphasis in the future development will be to combine the so far partly independently operating automated partial systems on the machine. Whereas by automizing individual functions in many cases only improvements in a certain direction can be achieved, these integrated systems will be of advantage to all sectors involved, such as:

- Ease of operation
- Improved performance of the machine
- Increased efficiency, especially by reduced fuel consumption
- Longer service life and maintenance intervals due to smoother load impact on the components.

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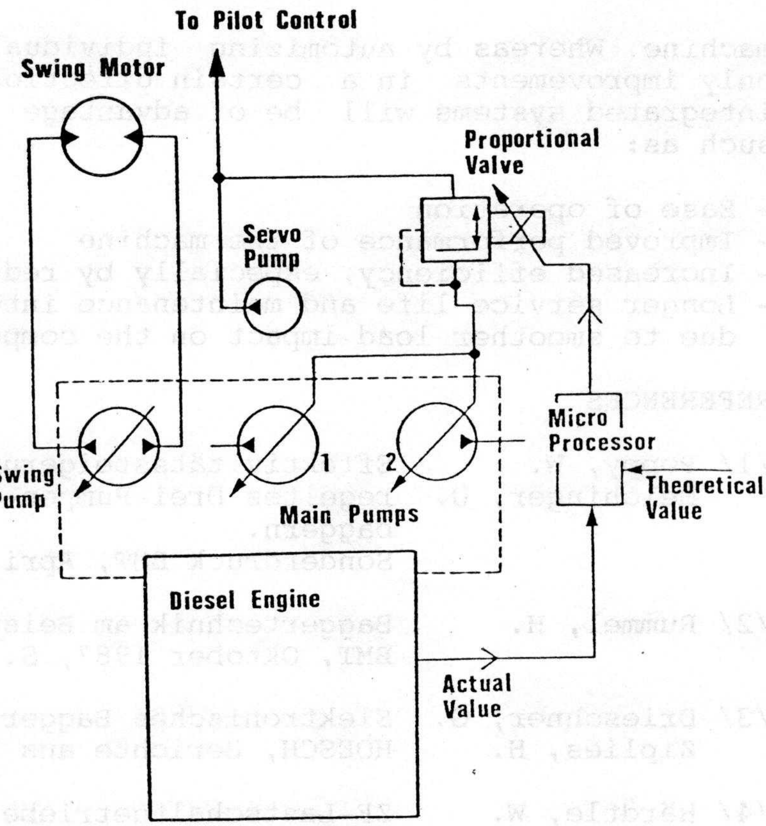
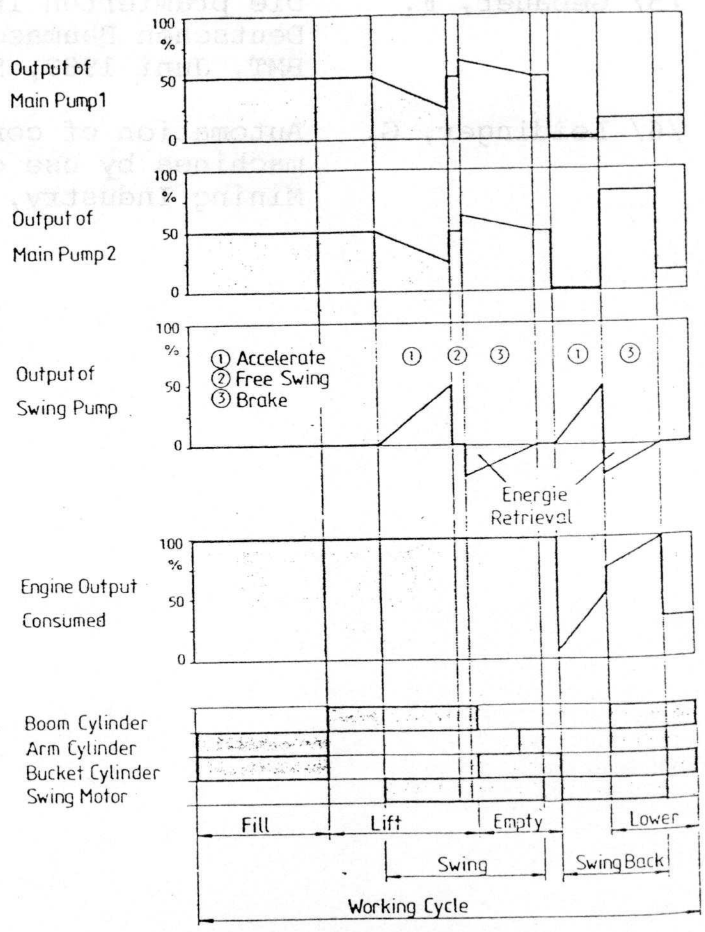


Set-up and function of the Pump-Managing-System

Figure 1



Time phasing of engine output and output consumed by an excavator's 3 pump system for a working cycle

Figure 2

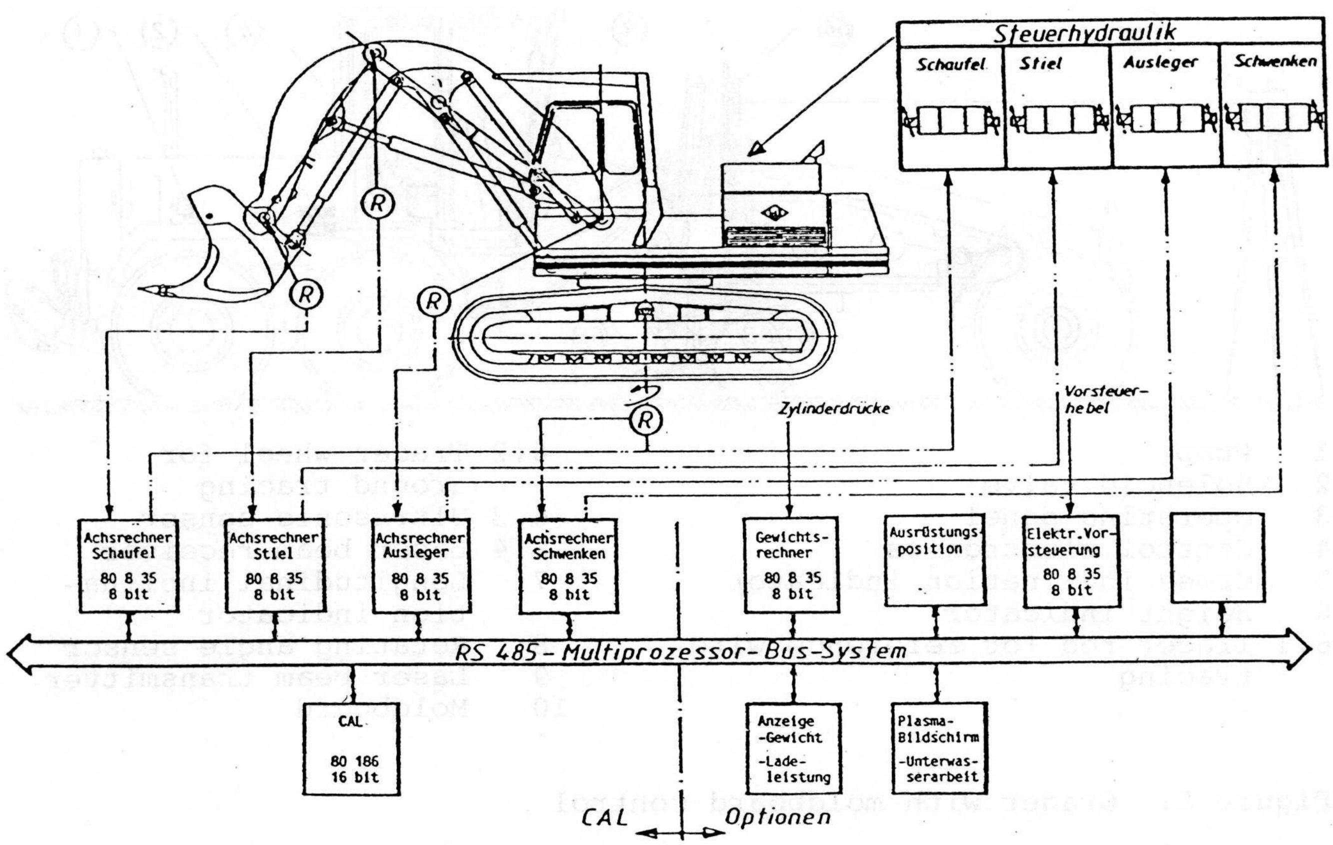


Figure 3: CAL-Illustration of an automatic excavator control

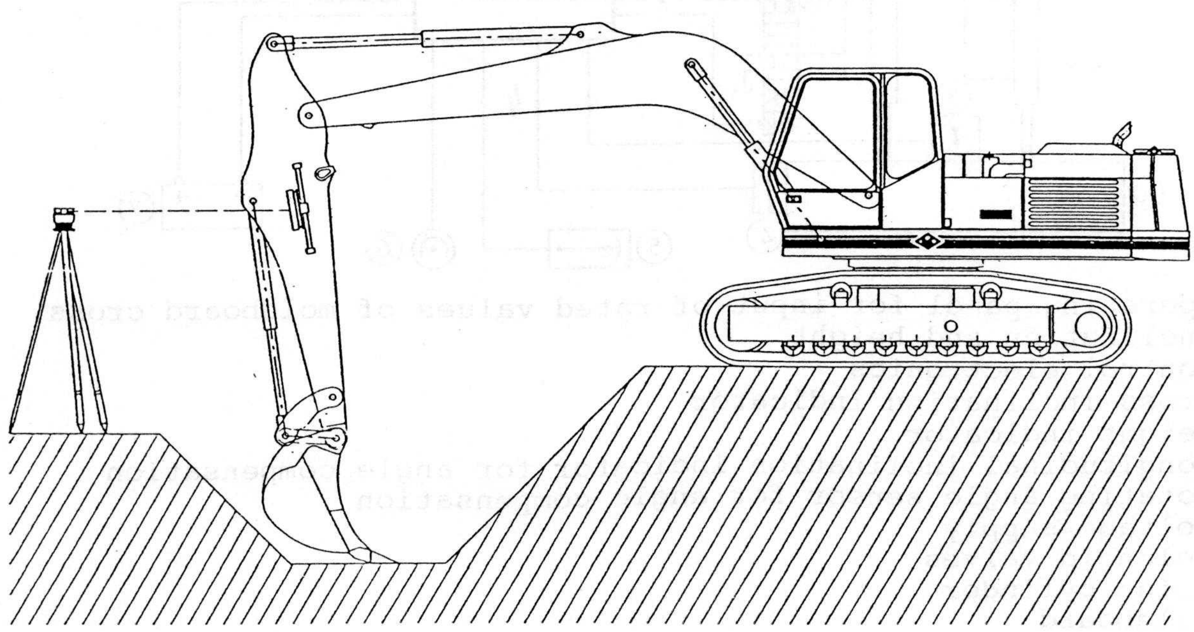
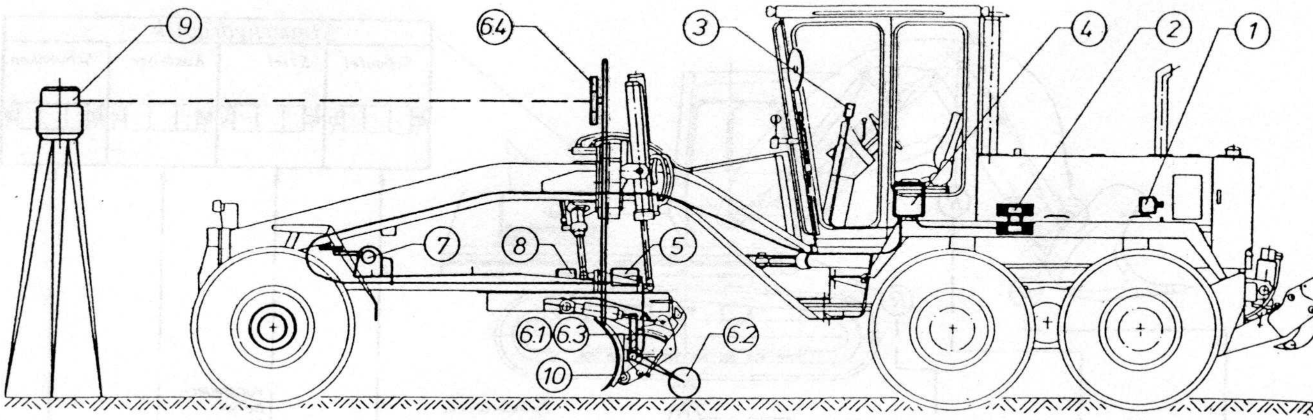
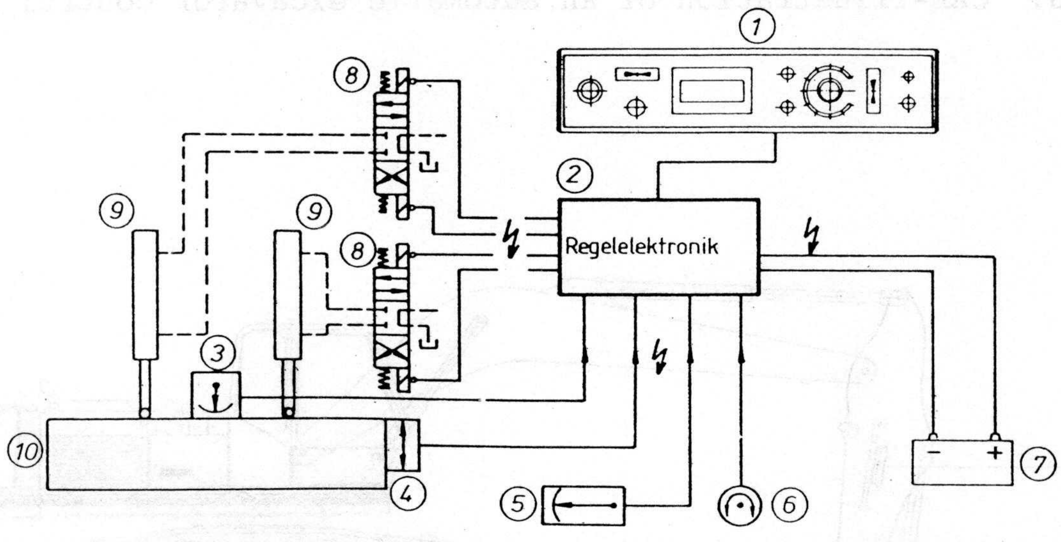


Figure 4: CAP-Computer assisted profiling with laser



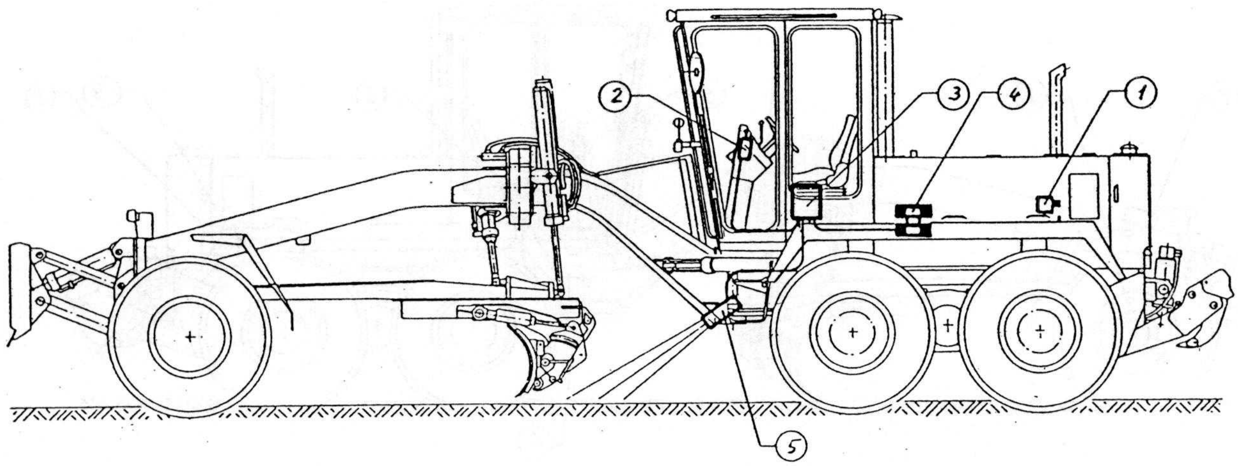
1 Pump
2 Solenoid valve
3 Operating panel
4 Control electronics
5 Cross inclination indicator
6 Height indicator
6.1 Tracer rod for reference wire tracing
6.2 Tracer wheel for ground tracing
6.3 Ultrasonic sensor
6.4 Laser beam receiver
7 Longitudinal inclination indicator
8 Rotating angle sensor
9 Laser beam transmitter
10 Moldboard

Figure 5: Grader with moldboard control



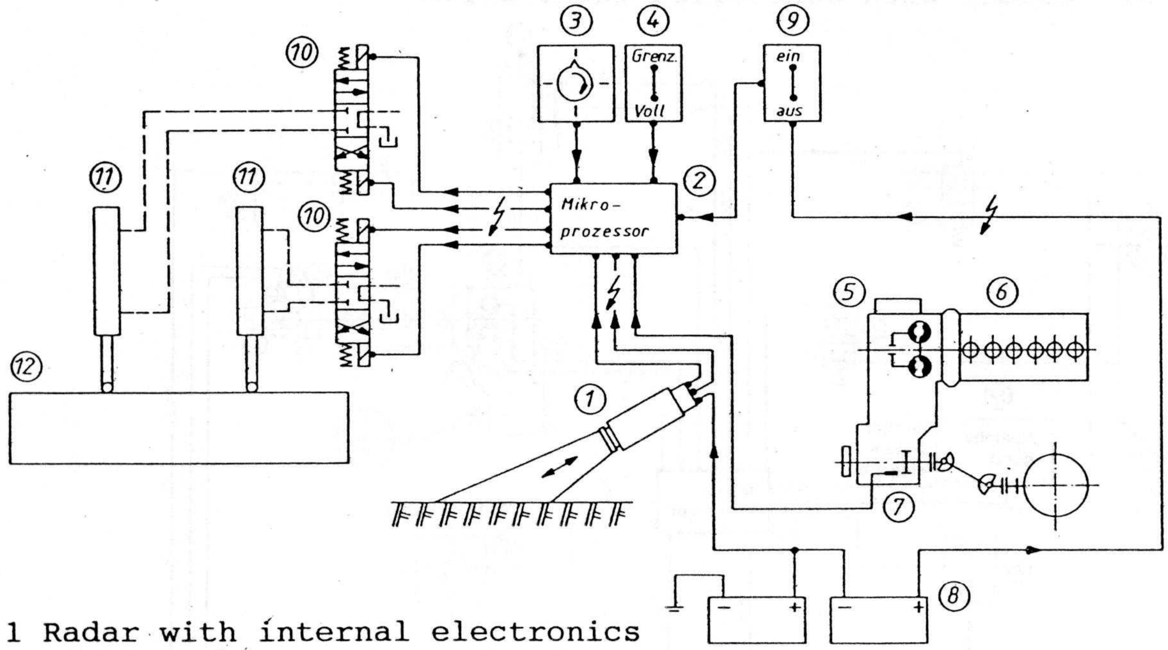
1 Operating panel for input of rated values of moldboard cross inclination and height
2 Control electronics
3 Cross inclination indicator
4 Height indicator
5 Longitudinal inclination indicator for angle compensation
6 Rotating angle sensor for angle compensation
7 Voltage supply
8 Solenoid valves
9 Hoist cylinder
10 Moldboard

Figure 6: Block diagram of the moldboard control system



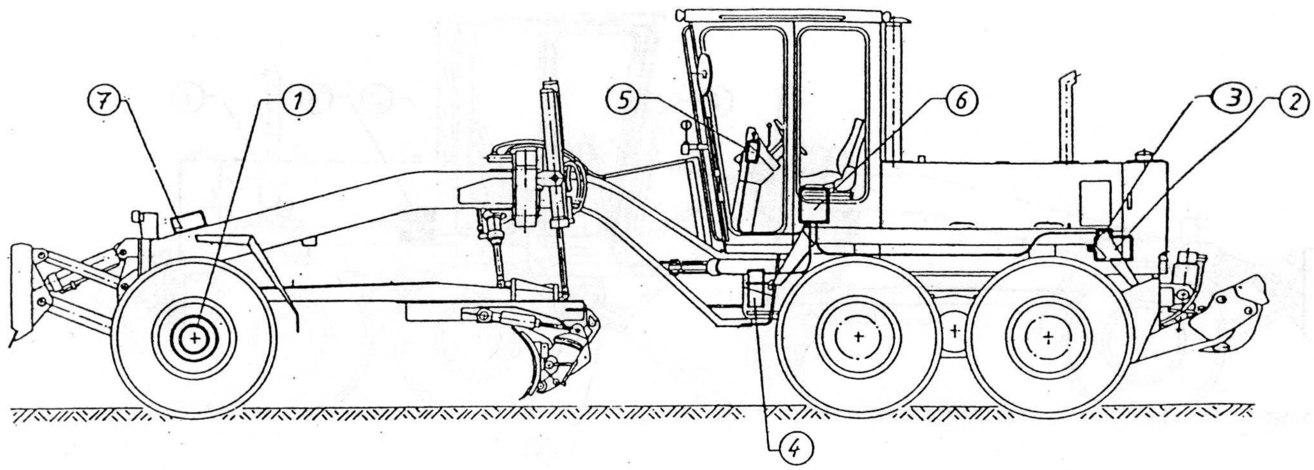
1 Pump
2 Operating panel
3 Control electronics
4 Solenoid valves for moldboard lift
5 Radar

Figure 7: Grader with anti-slip control by radar or sonar



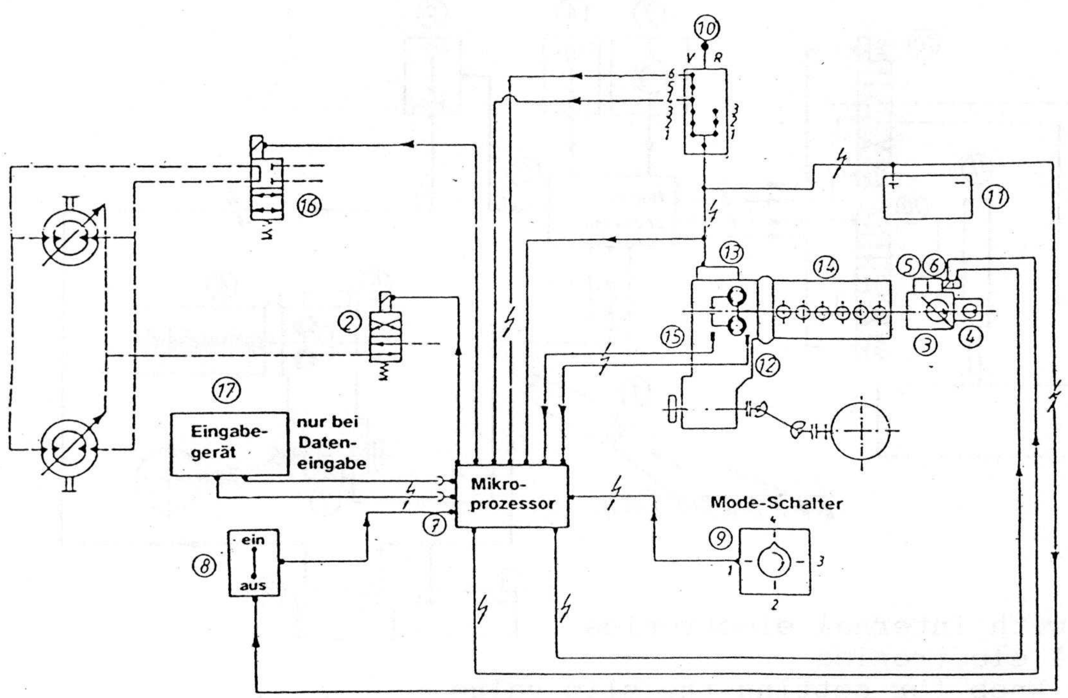
1 Radar with internal electronics
2 Control electronics
3 Rotary knob for setting the slip value
4 Switch for operating mode
5 Powershift transmission
6 Engine
7 Inductive sensor
8 Batteries
9 On/-off switch
10 Solenoid valve
11 Hoist cylinder
12 Moldboard

Figure 8: Block diagram for anti-slip control



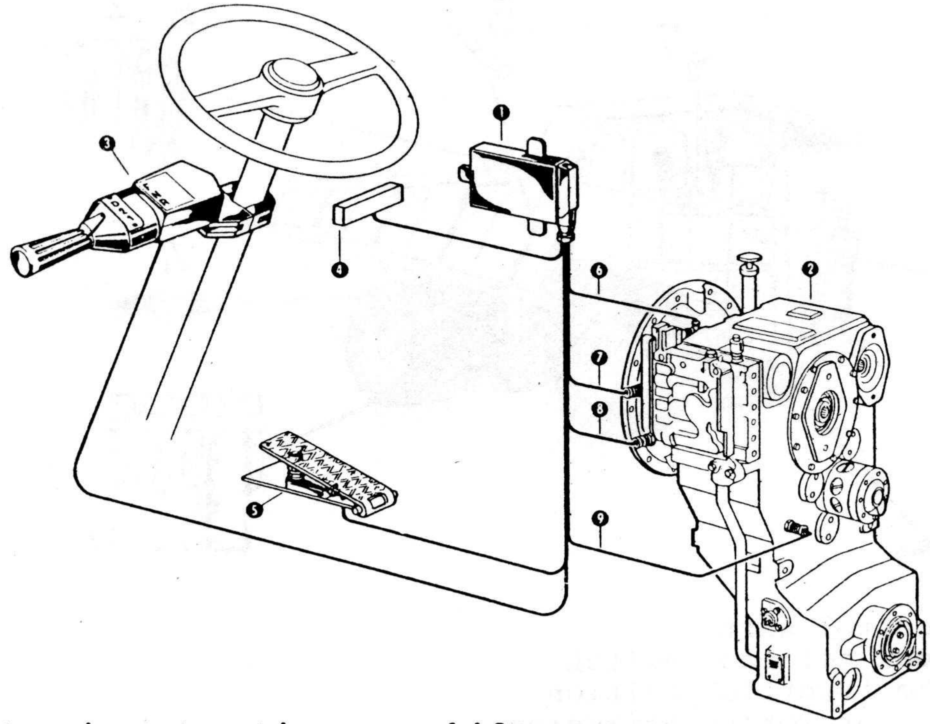
1 Hydromotors
2 Variable displacement pump
3 Electronic proportional valve
4 Valve block
5 Operating panel
6 Control electronics
7 Flow divider

Figure 9: Grader with controlled front drive



1 Wheel motors
2 Switch valve, wheel motor
3 Variable displacement pump
4 Feed pump
5 Pump regulator
6 Solenoid valves
7 Control electronics
8 Switch, front wheel drive
9 Aggressivity switch
10 Gear selector lever
11 Battery
12 Powershift transmission
13 Electro-hydr. control block
14 Diesel engine
15 Inductive sensor
16 Lock valve
17 Input device

Figure 10: Block diagram of front-wheel drive



1 Electronic automatic gear-shift system
2 Hydromedia powershift reversing transmission of the WG series
3 Gear selector switch
4 Electric power supply
5 Kick-down pedal
6 Cable - gear shift (solenoid valves)
7 Cable - torque converter lock-up clutch
8 Cable - inductive sensor, turbine revolution
9 Cable - inductive sensor, output shaft revolution

Figure 11: Electronic automatic shift for powershift transmissions

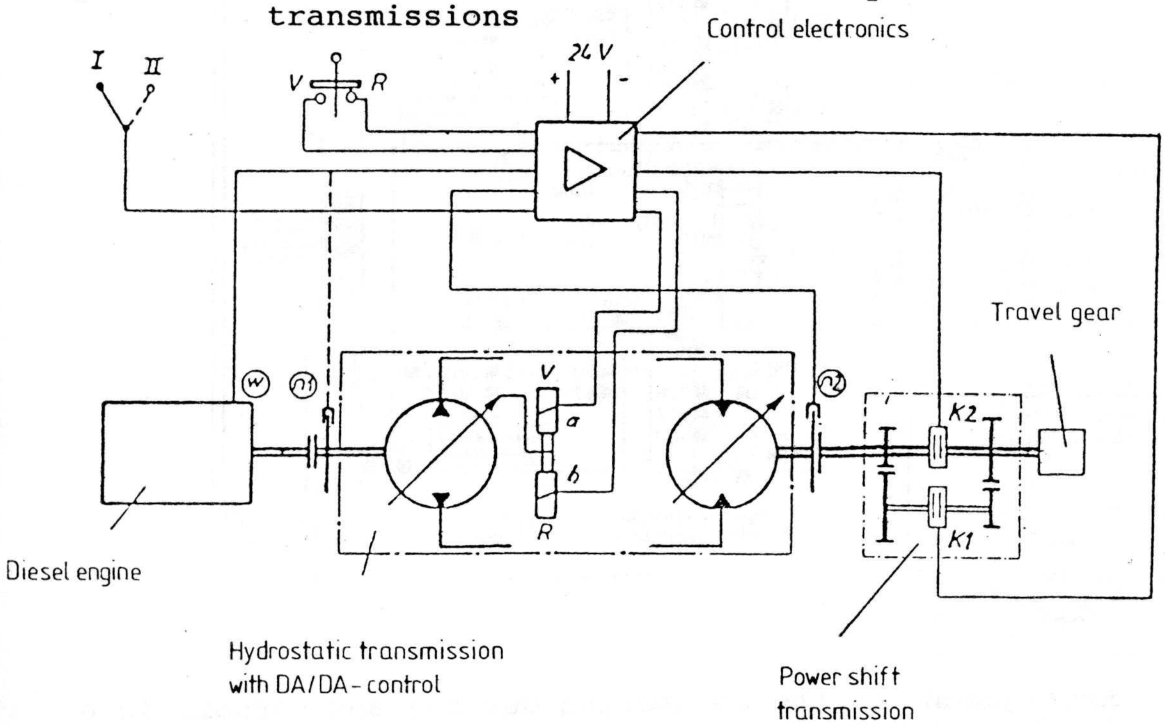
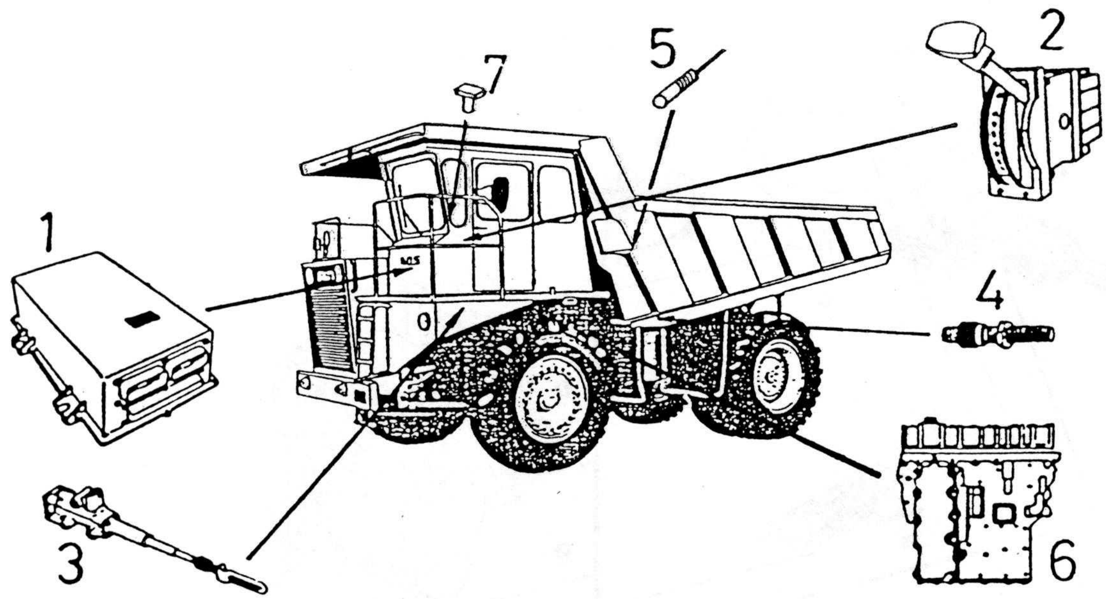


Figure 12: Electronically switched hydrostatic travelling



1 Electronic control unit
2 Electronic gear selector switch
3 Sensor for the throttle position
4 Electronic sensor for transmission
5 Retarder switch
6 Electro-hydraulic valve block
7 Warning light (CHECK TRANS)

Figure 13: Components for automatic transmission of dumpers

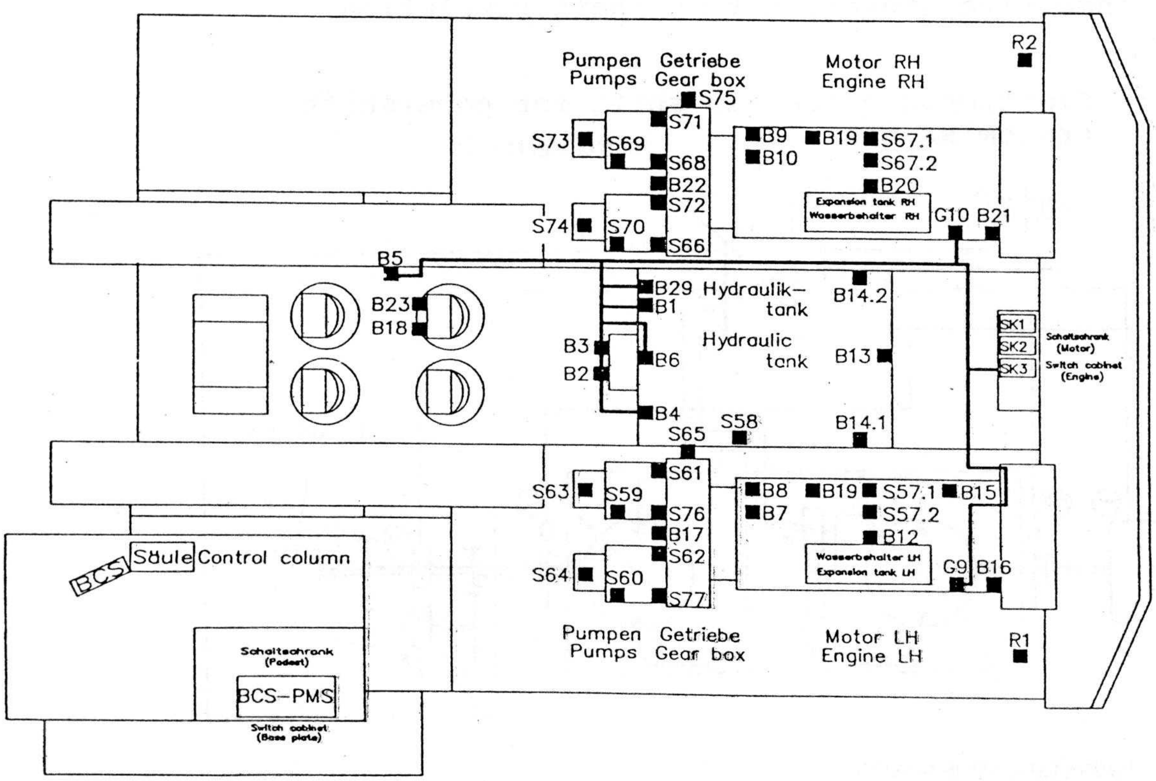


Figure 14: Arrangement of the monitoring devices and sensors in a large excavator.

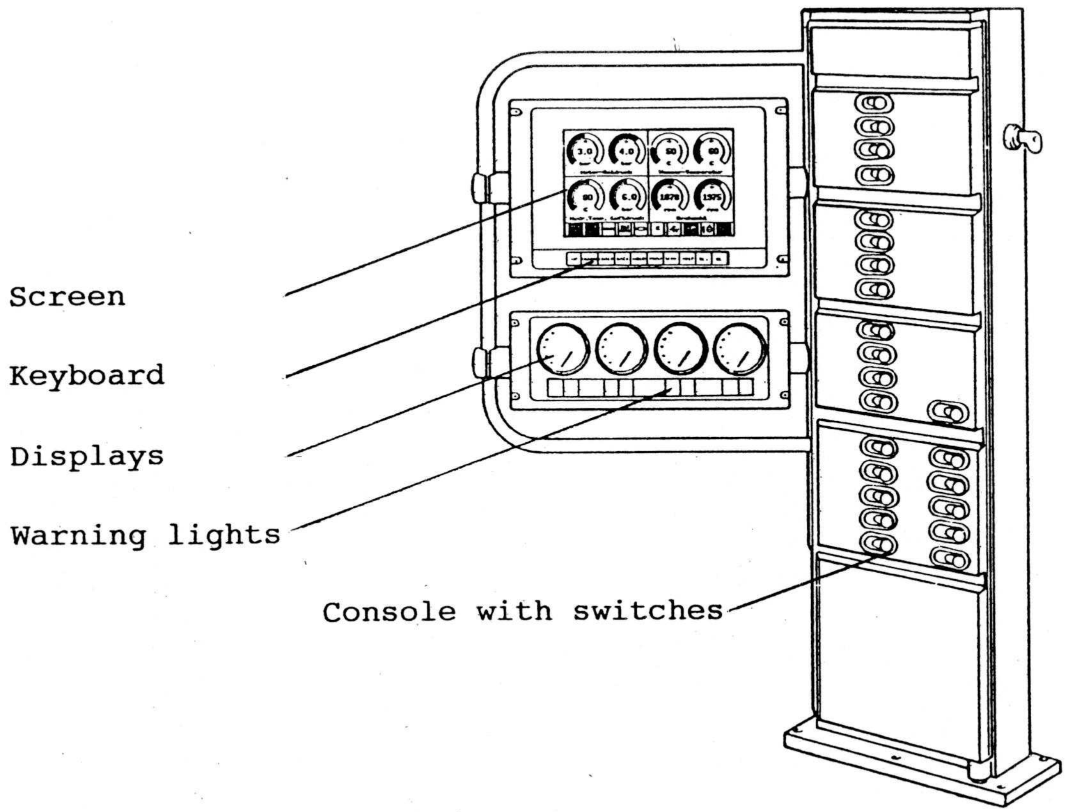


Figure 15: Board-Control System: System in the operator's cab

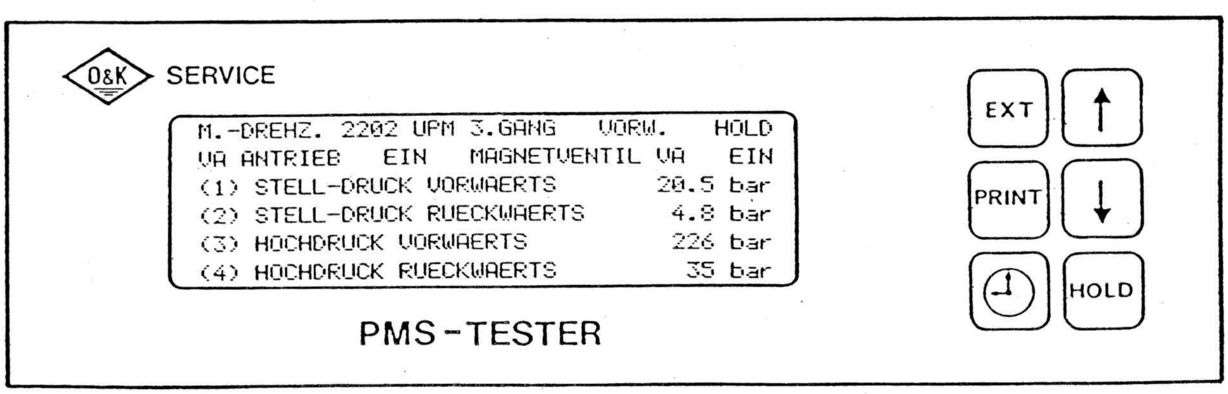


Figure 16: Display and keyboard of the test and input unit

AN ERGONOMIC ANALYSIS FRAMEWORK FOR CONSTRUCTION ROBOT PERFORMANCE REQUIREMENTS

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ABSTRACT

This paper presents a method for calculating a quantitative deterministic measure of the automated machine performance requirements based on the envisioned machine characteristics and available technology for a specific construction task application. An example application of the developed methodology to the analysis of a concrete placement task is provided. The developed method can be used to aid construction equipment manufacturers in evaluating the relative difficulty in regard to applying current automated equipment technology to selected construction work tasks.

1. INTRODUCTION

To date, the construction industry worldwide has little experience in the application of automation to on site construction processes. Also, no structured approach exists to analyze machine performance requirements for construction tasks before even partial task automation is considered. To streamline the development resources effectively, an identification of the machine performance requirements must be performed prior to considering automation of the traditionally human labor-performed tasks. This will facilitate rational decision-making regarding potential application of automation to the considered work task and increase the probability of achieving a feasible application. A structured methodology is needed for evaluating machine performance requirements of a construction task in the light of envisioned machine characteristics and equipment technology available. A major benefit of this methodology can be eventually achieved through a creation of a knowledge base containing construction robot characteristics and performance data. Such knowledge will aid the designers of automated construction equipment in understanding existing equipment and technology, and subsequently in new equipment designs. Such designs will be feasible where task requirements for a human laborer are demanding and the technology available to automate the given task is sufficient to meet the application needs.

This paper outlines a method for determining a quantitative deterministic measure of the machine performance requirements with the use of available robot technology. The method presented here is a part of a larger work analysis framework, containing both human and machine performance requirements in the execution of considered construction tasks. Within this framework, a corresponding method for determining the human performance requirements has also been developed (refer to reference 2).

Construction projects consist of a number of work operations. The operations can be further broken down into individual work processes[1]. A work process consists of a number of steps that must be performed to complete a construction operation. A hierarchical representation of the analysis of a construction task is presented in Figure 1. As shown, concrete construction operation includes the following processes: activity preparation (e.g., planning, layout of members, formwork placement, etc.), concrete placement, concrete finishing, concrete curing, and other processes (e.g., formwork stripping, patching, etc.)[4].

A process can be characterized by numerous tasks. A task identifies all the steps that must be performed to complete a process. For example, the tasks associated with the concrete placement process presented in Figure 1 are agitation of concrete mix, levelling of fresh concrete, measurement of levelness, screeding, and darbying.

An ergonomic analysis of each construction task can be performed to identify the work characteristics associated with the given task. These characteristics include: physical parameters such as elementary motions (e.g., translation, rotation, etc.), forces required, work positions, and maximum movement and velocity capabilities of a human worker; cognitive parameters such as precision, repetitiveness, and experience; and environmental constraints (e.g., ambient temperature, relative humidity, noise, etc.).

The ergonomic analysis data can be applied to the developed automation feasibility determination tools which measure both the human and machine performance requirements. A more complete description of the work analysis framework as applied to the human labor requirements to perform a task is contained in reference 2. In the subsequent section, a description of the machine performance requirement framework is presented.

2. MACHINE PERFORMANCE FRAMEWORK FOR CONSTRUCTION TASKS

A selection of appropriate machine parameters identified in reference 3 has been incorporated into the developed machine analysis framework for concrete construction tasks. The machine characteristics within the analysis framework is based on the knowledge of site conditions for the performance of the considered task. The framework for determining the machine performance requirements of selected construction tasks is summarized in Figure 2. As shown, the framework consists of 8 main parameters (i.e., size, body characteristics, arm characteristics, etc.). In some cases, the main parameter can be characterized by second-level parameters. For example, the robot "body characteristics" (BC) parameter consists of the "type" of body (e.g., prismatic, revolute, combined, or mobile) and the "movement capabilities" of the body (i.e., maximum movement in meters and velocity capabilities measured in mm/sec). These two second-level parameters combined give a relative measure of the robot "body characteristics" associated with a given system. Also shown in Figure 2 are the attributes associated with the main parameters and second-level parameters. For the ease of modeling and analysis, the parameters contained within the framework are assumed to be independent.

Each parameter at an appropriate level is evaluated according to an attribute score regarding the specific robot application under

FIGURE 1.--A Hierarchical Representation of the Analysis of a Construction Task

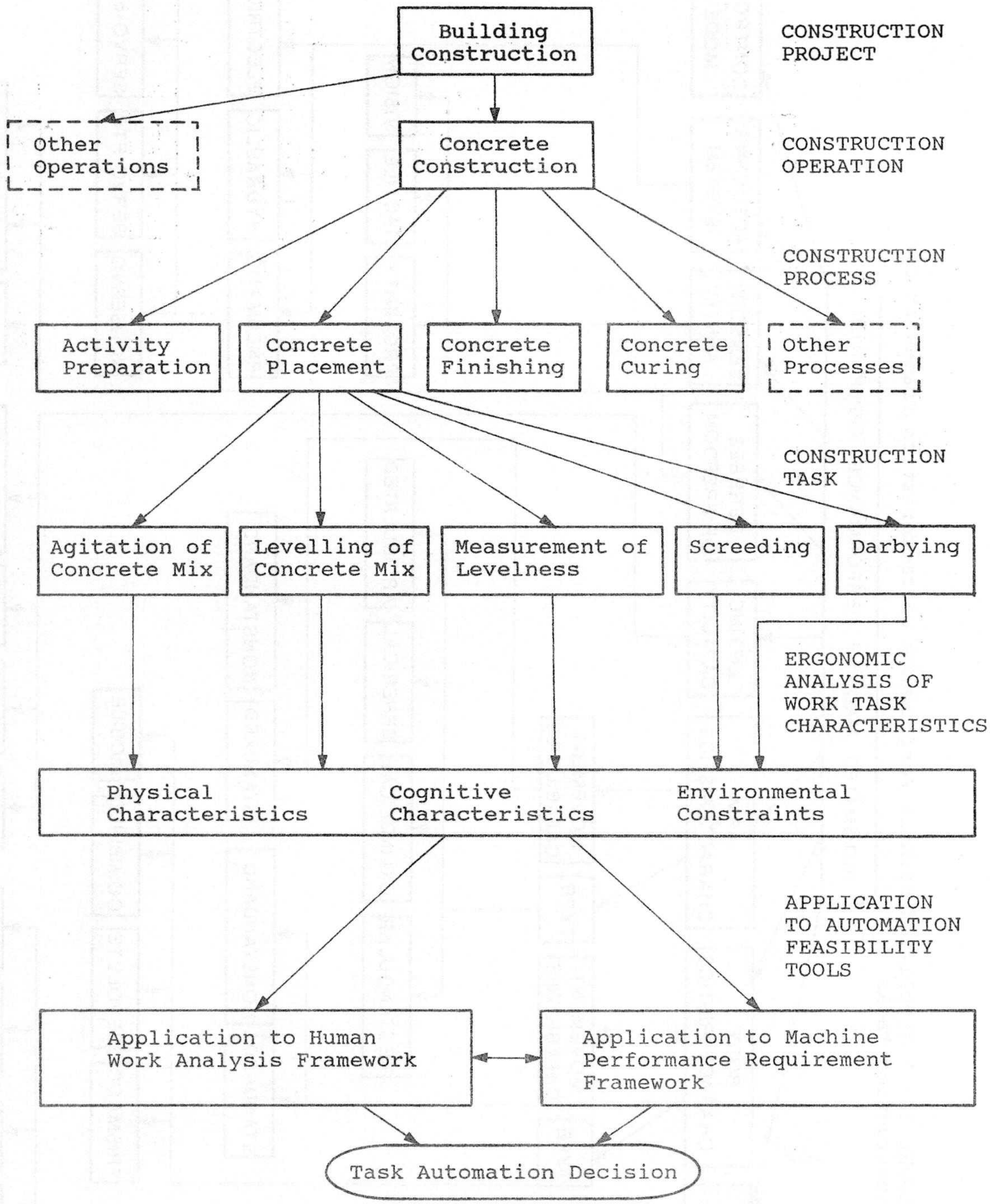
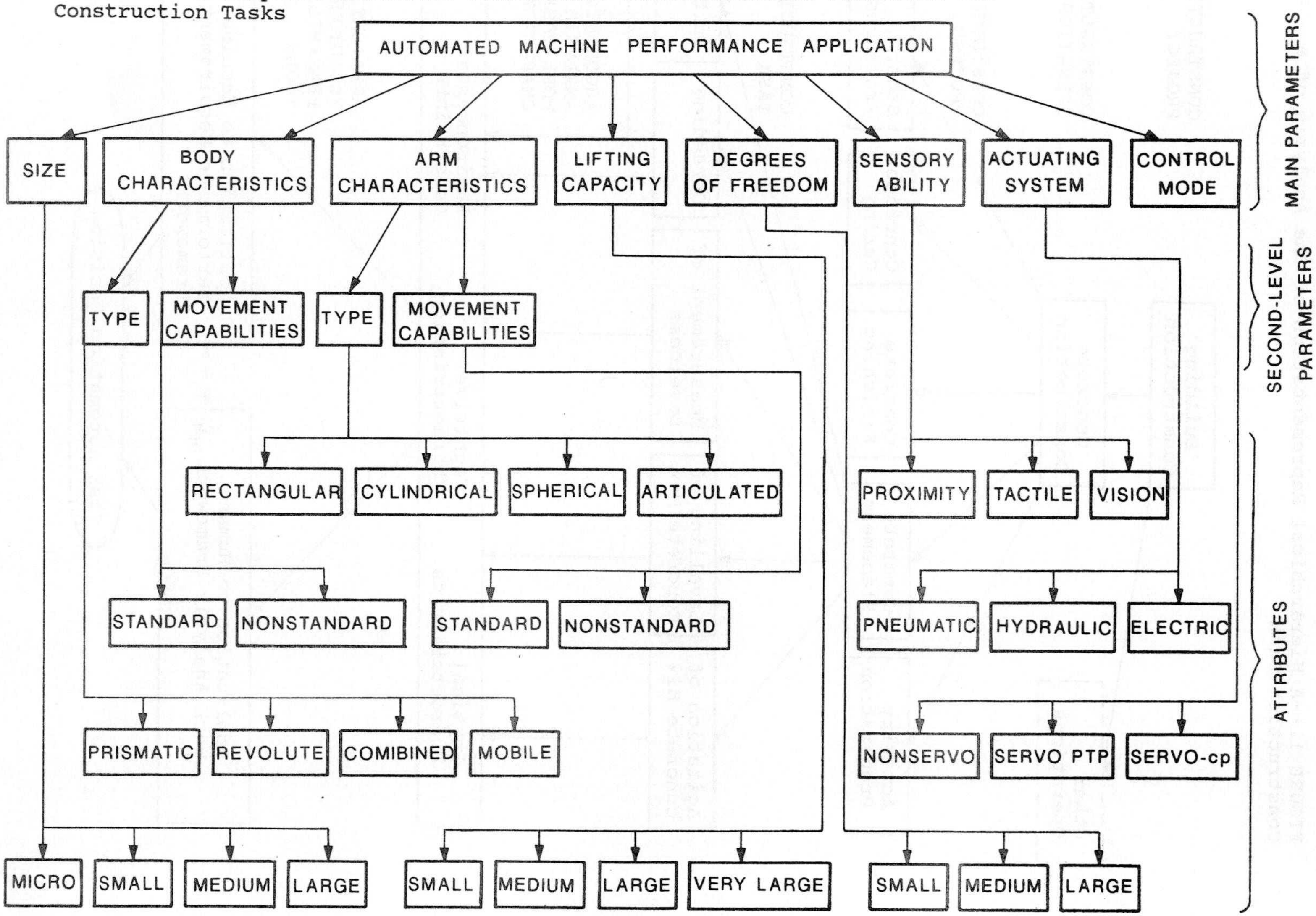


FIGURE 2.--A Simplified Machine Performance Characteristics Framework for Construction Tasks



consideration. For example, the main parameter robot "arm characteristics" (AC) has the following second-level parameters:

1. Type (weight of 0.50);

2. Movement capabilities (weight of 0.50).

"Type" (arm configuration) is described by:

1. Rectangular - 2 points;

2. Articulated - 2 points;

3. Cylindrical - 4 points;

4. Spherical - 6 points.

A composite scoring system has been developed which measures the performance requirements for the machine under consideration. The relative weights attached to each component within the framework are presented in Table 1. The weight associated with each component is representative of its automation difficulty and is provided only for illustration. The provided weights of the components may be revised for use with specific design conditions.

Table 2 presents the main parameters and second-level parameters with their respective attributes and the corresponding attribute values. To calculate the Automated Machine Performance Requirement Score (AMPRS), each parameter level attribute score is multiplied by its predetermined weight. The composite score is calculated by summing all main parameter scores (which in some cases are the aggregations of second-level parameter scores) multiplied by the main parameter weight. The formulas used to calculate the AMPR score are presented in Appendix II. An example illustration of this process is presented in the next section.

2.1. Example Application of Machine Performance Framework

To illustrate the process described in the previous section, an example application of a considered robot for the agitation of concrete mix is screened. The following parameters are assumed:

- Work envelope of 4m;
- Mobile robot body;
- Standard movement capability of robot body available in industry;
- Cylindrical arm configuration;
- Standard robot arm capabilities;
- Lifting capacity of 500N;
- Six degrees of freedom for the robot system;
- Tactile and proximity sensors;
- Electric actuating system;
- Servo continuous path (CP) control mode

The numerical values for each of these parameters are presented in Table 3. Using the example weights provided in Table 1, the composite score for the considered application is 3.40 which was calculated with Formula 3 in Appendix II. The final score provides a quantitative measure of the technical requirements to automate the existing work method when compared to the maximum score of 6.20 that can be achieved using the presented framework. Therefore, the example application can be viewed as possessing a relatively moderate level of difficulty based on the

TABLE 1.--Example Relative Weight of Framework Components

FRAMEWORK COMPONENTS (1)	RELATIVE WEIGHT (2)
Size (S)	0.10
Body Characteristics (BC)	0.10
Arm Characteristics (AC)	0.10
Lifting Capacity (LC)	0.20
Degrees of Freedom (DF)	0.10
Sensory Ability (SA)	0.20
Actuating System (AS)	0.10
Control Mode (CM)	0.10
BODY CHARACTERISTICS (BC)	
Type (BC_1)	0.50
Movement Capabilities (BC_2)	0.50
ARM CHARACTERISTICS (AC)	
Type (AC_1)	0.50
Movement Capabilities (AC_2)	0.50

TABLE 2.--Characterization of Framework Main Parameters

MAIN PARAMETERS (1)	SECOND-LEVEL PARAMETERS (2)	ATTRIBUTES (3)	ATTRIBUTE VALUE (POINTS) (4)
Size[a]		Micro:[b] less than or equal to 1m	6
		Small:[b] greater than 1m and less than 2m	4
		Medium:[b] greater than 2m and less than 5m	2
		Large:[b] greater than 5m	6
Body Characteristics	Type	Prismatic	2
		Revolute	2
		Combined	4
		Mobile	6

TABLE 2.--Characterization of Framework Main Parameters (Continued)

MAIN PARAMETERS (1)	SECOND-LEVEL PARAMETERS (2)	ATTRIBUTES (3)	ATTRIBUTE VALUE (POINTS) (4)
	Movement Capabilities	Standard[c]	2
		Non-Standard[c]	4
Arm Characteristics	Type	Rectangular	2
		Articulated	2
		Cylindrical	4
		Spherical	6
	Movement Capabilities	Standard[c]	2
		Non-Standard[c]	4
Lifting Capacity		Small:[d] less than 400N	2
		Medium:[d] greater than 400N and less than 3000N	4
		Large:[d] greater than 3000N and less than 10000N	6
		Very Large:[d] greater than 10000N	8
Degrees of Freedom		Small:[e] greater than 1 and less than 0	2
		Medium:[e] greater than 3 and less than 6	4
		Large:[e] greater than 6	6
Sensory Ability		Proximity (LED)	2
		Tactile	4
		Vision	8
Actuating System		Hydraulic	2
		Electric	3
		Pneumatic	4
Control Mode		Servo PTP	2
		Non-Servo	4
		Servo CP	4

[a] Main parameters are based on reference 3.
[b] Work envelope between the values listed in meters (m).
[c] Standard denotes capability achieved in existing automated systems.
[d] Lifting capacity between the values listed in Newtons (N).
[e] Number of degrees of freedom for the robot system.

TABLE 3.--Machine Performance Requirements for the Agitation of the Concrete Mix

MAIN PARAMETER	SECOND-LEVEL PARAMETERS	ATTRIBUTE	ATTRIBUTE VALUE	RELATIVE WEIGHT OF SECOND-LEVEL PARAMETERS	PRODUCT (4)x(5)	SUMMATION OF SECOND-LEVEL PARAMETER WITHIN MAIN PARAMETERS	RELATIVE WEIGHT OF MAIN PARAMETER	PRODUCT (7)x(8)	AMPRS SUMMATION OF COLUMN (9)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Size		Medium	2 (6)[a]						
Body Charac-teris-tics	Type Movement Capa-bilities	Mobile Standard	6 (6) 2 (4)	0.50 0.50	3 (3) 1 (2)	4.0 (5.0)	0.10 0.10	0.20 (0.60) 0.40 (0.50)	
Arm Charac-teris-tics	Type Movement Capa-bilities	Cylindrical Standard	4 (6) 2 (4)	0.50 0.50	2 (3) 1 (2)	3.0 (5.0)	0.10	0.30 (0.50)	
Lifting Capacity		Medium	4 (8)				0.20	0.80 (1.60)	
Degrees of Freedom		Medium	4 (6)				0.10	0.40 (0.60)	
Sensory Ability		Proximity Tactile $\frac{2+4}{2}$	3 (8)				0.20	0.60 (1.60)	
Actuating System		Electric	3 (4)				0.10	0.30 (0.40)	
Control Mode		Servo CP	4 (4)				0.10	0.40 (0.40)	3.40 (6.20)

[a] All values presented in parenthesis are maximum possible attribute values (from Table 2) obtained with the use of the presented method.

comparison of the two quantities of 3.40 and 6.20. The AMPRS score can be compared with the human requirement score (reference 2) to provide the decision maker with a basis for rational decision-making regarding the need and feasibility for automating the analyzed construction work task.

3. CONCLUSION

In this paper, a description of an ergonomic analysis approach to construction tasks has been presented. Subsequently, a framework for measuring automated machine performance requirements based on the machine characteristics for a specified construction task has been outlined. An example application utilizing the developed framework has also been presented.

A comparison between human[2] and machine requirements to perform a given task can be made. However, each framework consists of dissimilar parameters and units of measure. Nevertheless, the parameters that characterize the requirements for each respective type are relevant to each application.

The two quantities, human requirements to perform the task with traditional labor intensive methods and the machine requirements to perform the task (AMPRS) for a given application can be compared to determine if the current manual labor to perform a task should be automated. The recommendation to automate a particular task would be positive when a high score is obtained from the manual work analysis and a low score in the projected machine performance analysis.

The significance of the developed system is that a quantitative value reflecting the level of difficulty of task performance can be calculated to aid in the feasibility determination of construction task automation. Future research on tailoring this framework to specific classes of construction tasks will include, among others, investigation of structured procedures for determining the weights of individual components of the proposed robot work systems.

APPENDIX I.--References

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3. Nof, S. Y, Handbook of Industrial Robotics, Robot Ergonomics: Optimizing Robot Work, John Wiley & Sons, New York, N.Y., 1985, pp. 549-604.

4. Skibniewski, M. J., Lutz, J. D., Russell, J. S., Hijazi, A. and Sako, N. "Research on the Automation of Concrete Placement and Finishing," Technical Report, Purdue University, School of Civil Engineering, February 1988, pp. 187.

APPENDIX II.--Formulas For Determining Automated Machine Performance Requirement Score (AMPRS)

Given the following data:

- BC_1 = Robot Body Type, BC_2 = Movement Capabilities, the Body Characteristics (BC) can be calculated;

- AC_1 = Type of arm configuration, AC_2 = Movement Capabilities, the Arm Characteristics (AC) can be calculated;

$$BC = (0.50)\ BC_1 + (0.50)\ BC_2 \tag{1}$$

$$AC = (0.50)\ AC_1 + (0.50)\ AC_2 \tag{2}$$

- S = Size;

- LC = Lifting Capacity;

- DF = Degrees of Freedom;

- SA = Sensory Ability;

- AS = Actuating System;

- CM = Control Mode.

Given attribute values for all of the above parameters, the Automated Machine Performance Requirement Score (AMPRS) can be calculated.

$$AMPRS = (0.10)\ S + (0.10)\ BC + (0.10)\ AC + (0.20)\ LC + (0.10)\ DF + (0.20)\ SA + (0.10)\ AS + (0.10)\ CM \tag{3}$$