Flexible Automotive Strategy (FAST) for Hydrostatic Transmissions

M. Ruggeri
CEMOTER – C.N.R.
Via Canal Bianco, 28
44044 Cassana Ferrara - ITALY
(E-mail: ruggeri@cemoter.bo.cnr. It)

ABSTRACT

Starting from previous papers [1], where hydrostatic transmissions automotive controls functionalities were investigated, an embedded electronic control system was designed. It is based on a low cost electronic control unit, controlling a hydrostatic transmission with a variable displacement axial piston pump and an axial piston dual displacement motor. The pump displacement control strategy, which depends on diesel engine working point and delivery pressure, is based on a fully customisable engine performance map. Special control strategies superimposed on this strategy and depending on autorecognized working mode, that allowed excellent performance in the vehicle field test phase to be reached. Special diagnostic strategies were introduced, based on functional and congruence controls, relying on fault recovery systems, to maintain the system in a high safety condition and to modify automatically the system working mode in case of fault occurrence. This approach allows reduction of overall risks for the operator and the environment.

KEY WORDS

Hydrostatic Transmission, Electronic Control, Microcontroller, Proportional Valves.

NOMENCLATURE

Cl: closed loop
GND: Ground
I: Current
O.C.: Open Circuit
Ol: open loop
P: Pressure
Pm: delivery Pressure
PWM: Pulse Width Modulation
S.C.: Short Circuit
S.C. @ VBATT: Short Circuit at Battery Voltage
S.C. @ GND: Short Circuit at Ground
VBATT: Battery Voltage
Vv: Coil Valve Voltage

INTRODUCTION

An advantage of electronic systems, used in hydraulics and especially in power transmission, is the break of direct link between hydraulics physical laws, that leads the responses of the control systems, and their actions. Complex control functions usually require many hydraulics components and strong design effort, both in simulation and hydraulic circuit testing and tuning. They can be easily carried out using digital control units performing desired control laws without a direct dependency on hydraulic variables. However, the main problem using electronic systems is the lack of control

stability analysis methods when non-linear control systems are used. Therefore advantages offered by electronics systems must be evaluated and tested in order to avoid uncertainty in system's behaviour.
This paper does not describes a classical electronically controlled hydrostatic transmission but rather the addition of new functionalities to a hydrostatic transmission electronic control in order to:

- increase from the operator's view point the performance in terms of comfort, safety and ease of use;
- from the vehicle components view point reduce jerk and pressure overshoot induced driveline stress;
- enhance system flexibility, for easy adaptation to different vehicle types, functionalities, dimensions and power.

PLANT DESCRIPTION

The test vehicle used was a backhoe-loader, 35000 kg mass, equipped with a 33.7 Kw @ 2800 rpm diesel engine. The hydrostatic transmission, is consisting of a variable displacement 45 c.c. axial piston pump with two proportional electro-hydraulic valves and a dual displacement 65 c.c. axial piston motor with a on/off electro-hydraulic valve. Proportional and on/off valves are controlled by the electronic control system. The test vehicle is also equipped with a gear pump supplying implements and steering system. The driver sets the drive command using a lever that controls two digital input, identifying three possible states: forward drive, reverse drive and stop. The driver also controls the diesel engine accelerator pedal, a switch to inhibit the hydraulic motor displacement and an inching pedal used only as an optional command in the final proposed vehicle configuration. The sensing is provided by a pair of pressure transducers placed in both hydraulic circuit lines and a frequency sensor which acquires the hydraulic pump shaft speed.
The main goal of the project, was to design a new control strategy that can increase ease of use, comfort and safety for vehicles equipped with hydrostatic transmissions, and reduces stresses of mechanical parts. The main task of the control is the continuous supply of hydraulic power, without excessive jerks and pressure spikes. To achieve this, a special control strategy was designed to automatically control the vehicle direction, thus the system is able to self manage the reversal of direction of motion regardless of the engine working point and active torque, without excessive driveline mechanical stress.

ELECTRONIC SYSTEM

The electronic control system is an embedded control unit able to acquire up to 8 analog signals from the plant and to control up to 4 proportional valves (PWM command, maximum 2,7 A for each output) and 2 on/off electro-hydraulic valves. The microprocessor is a RISC 8 bit microcontroller, Microchip 16F877 with 8 Flash eprom Kbytes and 368 ram bytes (Figure 1).
The microcontroller is also equipped with 128 bytes of serial internal eeprom, for fault condition storage and auto-adaptive data. The electronic system is equipped with a fully CAN V 2.0 B compliant controller, to communicate in a Vehicle Area Network (VAN), if present. The embedded hardware can also be connected to either a 12 or 24 V electric power source (i.e. battery), and thus is adaptable for a wider application range. The battery voltage is monitored in order to have ratiometric measure of sensors and correct power in PWM output.

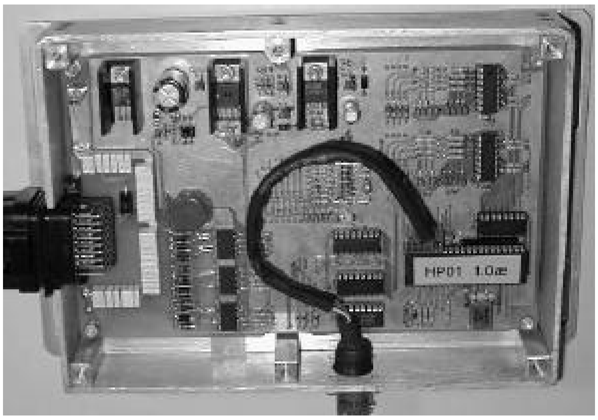

Figure 1 Control system hardware prototype

The key position signal permits to manage a self power-off to store in the serial eeprom memory the diagnosis results and the self-adapted control data. The hardware components that supply the power to proportional and on/off valves, are capable of diagnosing automatically the output status, performing fault diagnosis related to electrical valves status.
The fault recognized are:

- S.C. @ GND,
- S.C. @ VBATT,
- O.C.

This functionality is very important and will be dealt in the safety related section of this paper.

BASE CONTROL STRATEGY

The main control strategy is related to the transmission ratio n2/n1, where n1 is the engine (and axial piston pump) speed and n2 is the speed of motor in steady-state, depending on n1 and Pm, where Pm is the Delivery pressure of the transmission hydraulic circuit. The transmission ratio is a non linear function of the operator's command and of the working condition:

$$n2/n1 = f(n1, Pm) \qquad (1)$$

Due to absence of motor shaft speed sensor, n2 is only evaluated as a function of D1, D2 and Pm, where D1 is axial piston pump displacement, D2 is the axial piston motor displacement and Pm is the delivery pressure.

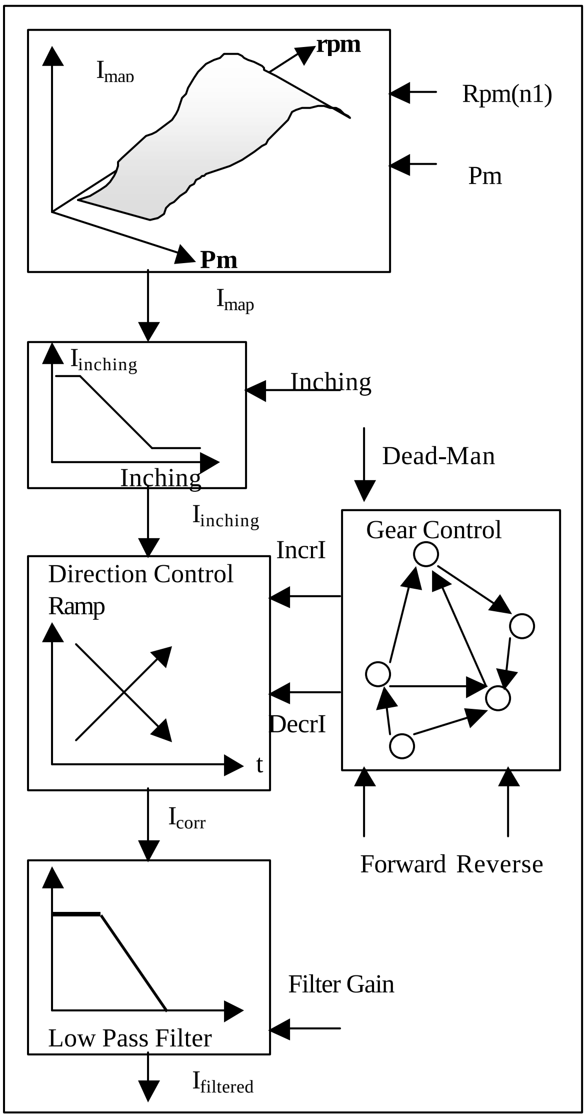

Figure 2 open loop control function scheme

The base transmission ratio computation is based on a matrix interpolation of pump displacement map (Figure 2), over n1 and Pm breakpoints (16 n1 breakpoints and 12 Pm breakpoints), executed by the microcontroller in run time every 10 ms. The breakpoint values are obtained by a fuzzy tuning system in a remote tuning device on a PC based platform, Figure 3, following the driving feeling of a test driver. The first vehicle configuration include an inching pedal, to rescale the transmission ratio calculated by the matrix values interpolation. A function block with an offset correction, based on the inching pedal potentiometer sensor acquisition, is introduced in the open loop transmission ratio calculation chain. The displacement values are proportional to transmission ratio, because the desired displacement values are obtained in the real operating conditions and thus include effect of hydraulic losses. To avoid valve command spikes and to control the dynamic displacement variation, a low pass filter with gain depending on Pm is introduced. Filter gain is the result of a linear interpolation of 8 gain breakpoint versus 8 delivery pressure breakpoint (Figure 2). A pump displacement variation control strategy, controls the vehicle direction reversal, following the driver's request, acquired by the digital switch position. The proportional valves that regulate pump displacement are closed to stop the vehicle, following a maximum displacement speed variation envelope, till the vehicle stop. Sequentially the opposite valve is opened following a different maximum displacement speed variation envelope, depending from the engine working point, till the steady state value from the matrix interpolation is reached. The control of the vehicle direction of motion is supervised by a finite state machine control, executed in run time by the microcontroller.

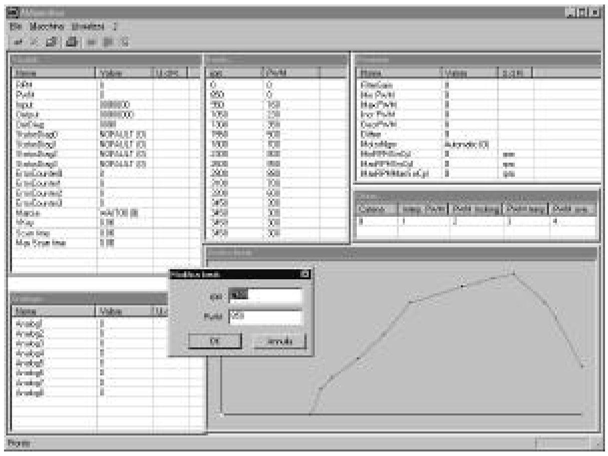

Figure 3 PC based tuning system

MANAGEMENT OF VEHICLE DIRECTION OF MOTION

The open loop transmission ratio control chain (Figure 2) controls pump displacement in a steady-state condition and without direction of motion command switch; the dynamic direction switching control, with the uncontrolled diesel engine speed (n1 is a uncontrolled variable), is managed by different control function selected using a finite state machine that relates actual direction and driver's requested direction. The most important plant variable independent from the electronic system is n1, that can be used by the driver to set the engine working point in a high torque, in order to have power for auxiliary functions, even if the vehicle is in a direction switching phase. In these conditions, the engine active torque is high and the base map interpolated pump displacement value is also high, and therefore not corresponding to the driver's request. The finite state machine at the first level (Figure 4) manages the system initialization and inhibits the vehicle movement if some fault is present in the direction external commands or if the external device that controls the driver presence on the vehicle called "dead man" is switched off. If normal operation conditions are identified, the hierarchical finite state machine manager enables the machine in Figure 5, where the actual vehicle direction is compared with direction request of the driver. If the driver direction request is equal to the actual vehicle direction then the finite state machine enables the pump proportional valve command of the open loop chain. On the other hand, if the actual vehicle direction is different from the request of the driver, the finite state machine enables the boundary envelope that limits the maximum displacement acceleration.

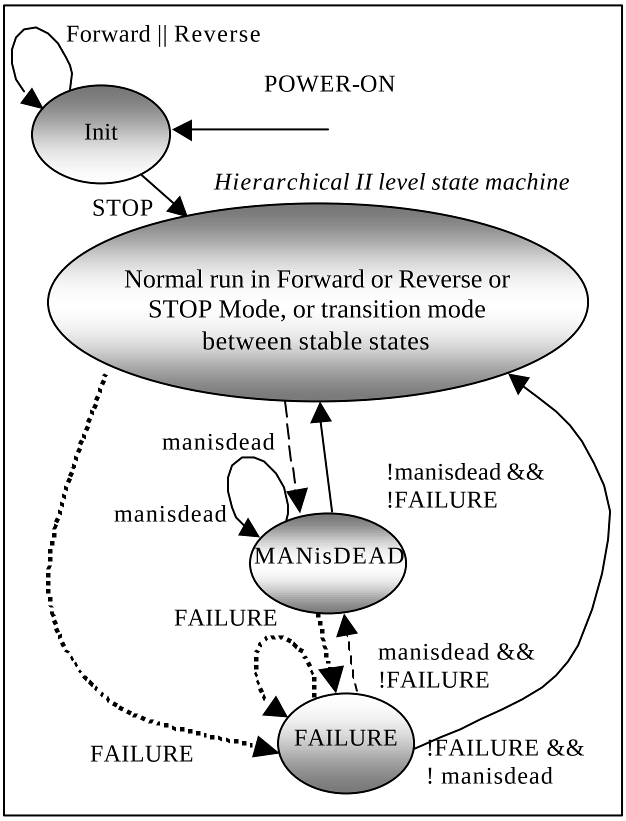

Figure 4 Power On and fault condition management

In Figure 5 the conditions that cause the state transitions are displayed. The state machine outputs are the correct vehicle direction and the relevant valve to be opened and controlled. The control mode is defined by a third level state machine that is displayed in Figure 6 for the forward direction (the reverse state machine is identical). This hierarchical third level state machine manages the vehicle speed starting from a steady condition (state STOP) till the forward condition when the open loop displacement set point is reached, passing through a state where maximum displacement slope envelopes are enabled. Depending on the transition envelopes (i.e. from STOP to FORWARD or from FORWARD to STOP) are different. This control strategy to guarantees a change in vehicle direction of motion without driveline stress on any engine working point set by the operator. Another third level finite state machine is managed by the system in order to guarantee that the fault condition recovery management is performed.

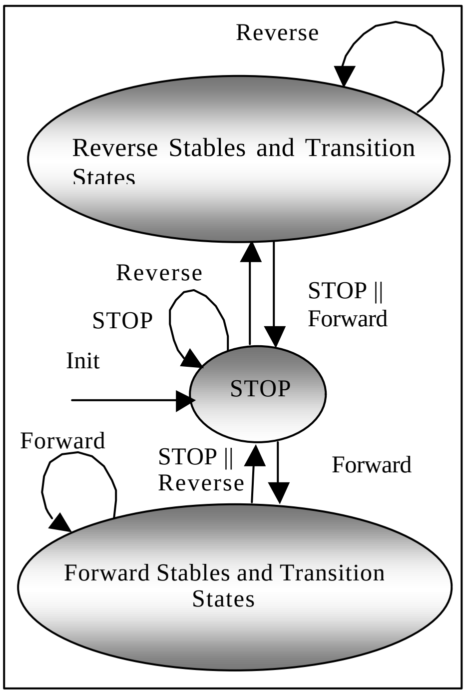

Figure 5 Second level state machine switch between opposite directions and stop condition

This state machine is identical with the one shown in Figure 6 with the exception that the recovery from the STOP state is possible only with an electronic system power-off/power-on switch. This is due to ensure that the operator understood that a fault has occurred and that any attempt to repeat the operation can cause the system to go in fault condition. Only the most severe faults lead to a vehicle halt. Depending on the fault type the recovery can be a speed limitation, a vehicle halt or simply a message to the driver (switching on the fault lamp). Due to hardware limitations it is not possible to guarantee autonomous vehicle movement in both directions in all fault conditions.

PROPORTIONAL VALVES CURRENT FEEDBACK

The displacement set point computation chain provide a current value that is converted in the corresponding PWM duty cycle value by a function:

$$
\begin{aligned}
Vv &= Rv * Isp \\
DC &= Vbatt / Vv
\end{aligned}
\qquad (2)
$$

Where *Rv* is the Valve resistance, *Isp* is the open loop chain current set point, *DC* is the *PWM* duty cycle and *Vbatt* is the battery voltage acquired by the microcontroller. In default environment condition this duty cycle corresponds to a desired current supplied to the proportional valves. Unfortunately, due to high

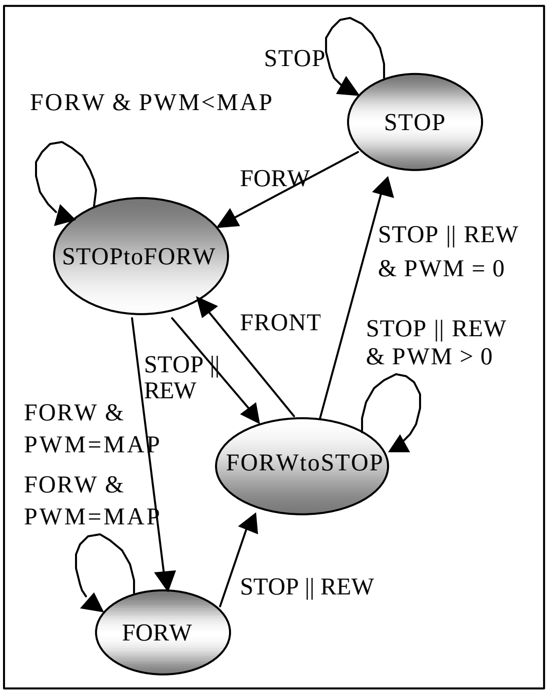

Figure 6 Third level state machine, transmission ratio variation envelope

range of variation in vehicle working conditions, the simple open loop is not enough to guarantee the right current supply. Therefore a current closed loop, based on a current sensing resistance that generates a voltage proportional to the valve current is introduced.
The open loop current set point *Iol* is compared with the real current value *Ir* acquired by the current sense. The difference is used to create a closed loop current correction using a PI controller:

$$
\begin{aligned}
e(t) &= Ir(t) - Iol(t) \\
Icl &= Kp * e(t) + Ki \int e(t)dt
\end{aligned}
\qquad (3)
$$

Experimental results indicate that error in current supply is essentially due to temperature variation and not to the engine and pump working points. As the error variation is slow and a linear controller with a memory factor due to Integral correction in (3) is enough to reach the desired performance in current supply. In order to further reduce the error valve resistance and temperature evaluation is performed. This implies starting the valve control, supplying a fixed PWM duty cycle and measuring current feedback. In this way equations (2) will introduce a minimum error also at the very first current supply.

HYDRAULIC MOTOR MANAGEMENT

The considered low cost application is equipped with dual displacement axial piston hydraulic motor. The motor displacement switch is controlled by the electronic system using a digital command to a electro-hydraulic on/off valve. The motor displacement switch creates a discontinuity in the hydraulic transmission ratio characteristic. The dual motor reduces flexibility of the system, the vehicle ease of use and the operator's driving feeling. Therefore usually the displacement switch is used only as vehicle mode selector with a manual command enabled only at a very low speed or in a steady vehicle operation. The switching is automatically managed by the electronic system and is combined with a transitory adaptation of pump displacement in order to reduce the negative effects (jerk) of motor displacement variation and discontinuity in the transmission ratio characteristic. Following automatic motor displacement switch control methods were tested using as input:

1. hydraulic circuit delivery pressure with hysteresis,
2. diesel engine speed (and pump speed) with hysteresis,
3. pump displacement (implicitly function of diesel engine speed and delivery pressure) with hysteresis,
4. the pressure difference in both hydraulic transmission lines with hysteresis.

Some of these methods performed better in some tests and worse in others.
Better results were obtained using method 2 and 4, but 2 was better in road vehicle transfer, whilst the 4 gave better results during loading and excavation with high transmission load. Method 2 is not fast enough in displacement changing to permit a quick switching in case of transmission overload, even if the base map give pump displacement values function of engine speed and delivery pressure breakpoints, due to driveability filters. Conversely the driver's feeling for driveability in road travel was better than that in strategy 4. Best performance solution was identified using the "old" manual motor displacement switch command to select the vehicle working mode, thus selecting the automatic switching method between 2 and 4. For safety reasons the switching method selection is disabled at high vehicle speed. It was found

that, using this selection, the inching pedal command previously introduced is no longer necessary and consequently vehicle ease of use is increased.

SAFETY AND DEPENDABILITY CONTROL SYSTEMS (SDCS)

The electronic control system actuates the pump displacement control proportional valves and motor displacement switch on/off valve commands. These commands are a result of sensor acquisitions and external commands given by the operator. In case of sensor damage or drift the system can issue wrong or dangerous commands. In order not to endanger either operator nor environment, safety diagnosis control functions are introduced. All sensors are individually diagnosed with respect to physical limits reachable in the vehicle environment, and congruence diagnosis are performed in order to verify the entire set of environment and vehicle information acquired by the microcontroller.

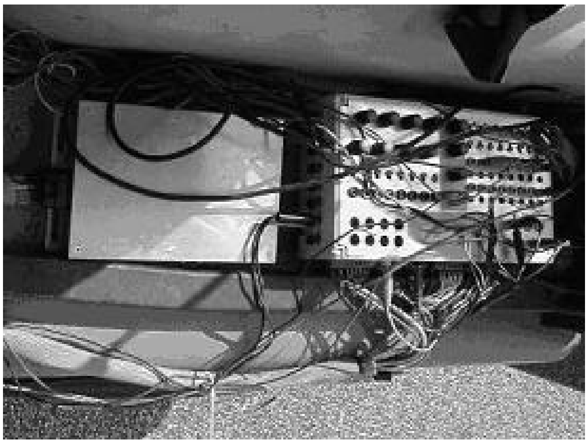

Figure 7 Test Box and control unit on the test vehicle

Fault recovery functions are activated in case of fault occurrence, in order to control the vehicle in a safe motion condition. Fault recovery depends on the fault severity and ranges from a simple fault lamp switch-on, to the complete vehicle stop, like for example in case of “operator’s presence” switch failure. The main criteria in fault recovery application is the transmission performance reduction in a measure proportional to the fault severity defined by the possibility of transmission system to correctly react to the operator’s commands. Similarly the output commands are diagnosed directly from the electronic power amplifier devices. In case of fault identification special electronic components are disabled to avoid short circuit on the proportional valves coils. Information congruence diagnosis are also performed using current feedback. In practice it means controlling the *Icl* current correction value in (3). When the $Icl \geq Isat$, where *Isat* is a saturation value, then the electronic system detects a coil circuit drift or damage, identified by the high current correction to the default value (from the open loop chain). In case of hydraulic motor displacement switch command fault the motor can be in a maximum or minimum displacement but the system can react correctly to the operator’s commands. Therefore the appropriate fault recovery is a hydrostatic transmission performance reduction, bounding the maximum pump displacement under a specific curve $D1 = f(rpm)$, engine speed function dependent. During the vehicle field test phase, external component faults are induced using a test box interface between electronic control unit and sensors and actuators (Figure 7). In the entire set of tests the system was able to react correctly to fault presence configuring the control actions in order to reduce the system performance and thus to avoid unsafe vehicle conditions for both operator and environment.

CONCLUSIONS

The FAST electronic unit is a versatile and flexible hydrostatic transmission control system, capable to control different displacement hydrostatic transmissions, coupled with different power engines, and different vehicle types. The electronic system flexibility permits to configure control functions in various sets of parameters and thus to satisfy the feeling of many test drivers. The presented strategies permit to establish that a good driving feeling can be associated with a good torque management if handled by a non linear strategy depending on engine speed and external loads. The jerk reduction in all vehicles working operations, and the reduction in the number of operator’s actions required during a shift, helps to improve the quality of work and gives the added value to this electronic embedded control system. It offers a more flexible system, with high level safety controls standards, at a lower cost with respect to traditional hydrostatic tractions. The system flexibility enlarges the possible range of applications to different machines and architectures, i.e. multiple motors or continuously variable motor displacement. Applications where pump swashplate position feedback or wheels speed feedback are accounted for, though not used, and can be fitted in the system, in order to guarantee the performance during the entire transmission life cycle, in order to compensate the aging effects.

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