Chapter

Hybrid Steering Systems for Automotive Applications

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Abstract

The paper presents the results of the researches performed in order to find out the static and dynamic performances of some recent types of hybrid electrohydraulic servomechanisms. The new concept was generated by the needs of the modern aerospace technology called "flight by wire", directed to the use of compact actuators composed mainly by a brushless motor driving a hydrostatic pump connected in a close loop with a hydraulic cylinder. The numerical simulations performed with Simcenter Amesim language pointed out the possibility of saving a lot of energy with this new concept, already used on civil airplanes and fighters. The new wave of autonomous driving generated a lot of combinations of electric and hydraulic components, according the peculiarities of applications. The authors studied the accuracy of the hybrid steering system of an articulated tractor based on a digital industrial servo valve combined with an ORBITROL standard unit. The structure of the last generation of the trucks hybrid steering systems was also studied, taking into account the real performances of each component. Finally, the effect of the strong penetration of the hybrid servo systems in the automotive manufacturing systems is assessed.

Keywords: energy saving, hybrid electrohydraulic servo systems, modeling, simulation, experimental validation

1. Introduction

The classical electrohydraulic servomechanisms, which include different types of high-speed two or three-stages servo valves (with flapper - nozzles, jet - pipes or piezo ceramic actuators) are still widely used in high performance control systems due to their very high dynamics reaching even 1000 Hz. However, the complex and expensive maintenance program, and the low overall energy efficiency due to the lamination of the fluid are strong drawbacks. The maximum efficiency of a classical hydraulic position servo system is lower than 65%. Consequently, all the advanced fluid control systems include oil coolers, and use special synthetic fluids for wide temperature ranges. In spite of these peculiarities, the modern servo valves offer minor time constants, which allow a high positioning accuracy. In the recent evolution of the electrohydraulic servo systems two important structural improvements can be pointed out:

a. The replacement of the classical servo valves by proportional directional flow control valves in different industrial applications (Rexroth, from 1989).

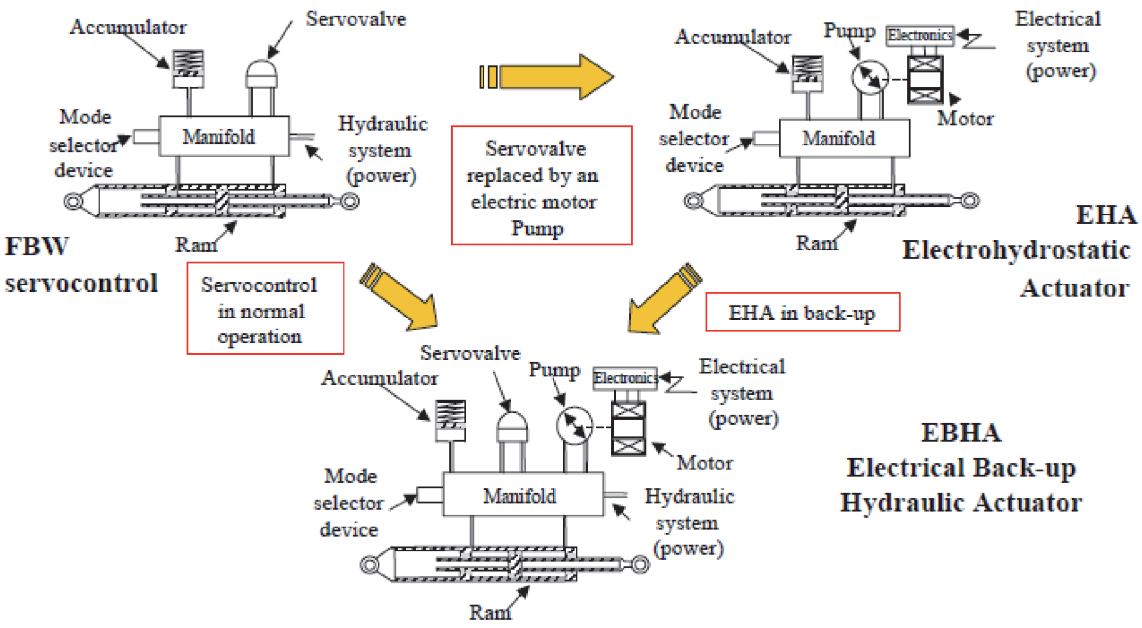
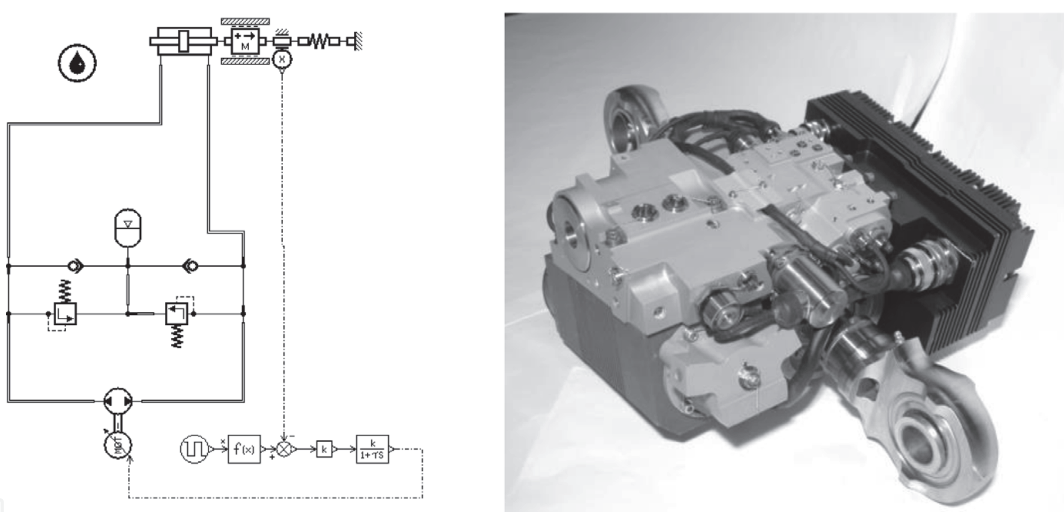


Figure 1.
Symmetrical structures of classical and hybrid electrohydraulic servos.



a) b)

Figure 2.
Structure of a hybrid servomechanism designed for actuating the ailerons of A380: (a) Basic hydraulic diagram; (b) Main view of assembly.

b. The replacement of any kind of servo valves by a bidirectional reversible volumetric pump driven with a brushless motor controlled by power electronics (Airbus, from 2005). This evolution is presented in **Figure 1** for symmetric actuators [1, 2]. **Figure 2** shows the hydraulic diagram, and the main view of A380 ailerons servos [1, 2].

2. Dynamics of a basic hybrid servomechanism

The assessment of the static and dynamic behavior of a hybrid servomechanism was performed by numerical simulation using Simcenter Amesim language produced by SIEMENS PLM Software [3, 4]. The simplified simulation network is shown in **Figure 2a**. The real hydro mechanical diagram of the system, proposed by Prof. J.-Ch. Mare in 2013 [5], shows a much more complex mechatronic system, with a mode selector (active or damping), a differential pressure transducer for the main loop, a rudder angle transducer, some hydraulic resistances modeling the system leakages etc. (**Figures 3** and **4**).

The core of the system is simple, but the whole assembly looks like a F1 hydraulic system with nine complex control loops: Power Steering, Gearshift Clutch, Differential, and Reverse gear, DRS, Brake by Wire, Throttle Inlet valves, and Turbo Wastegate. All of them are supplied in close loop by a single Parker swash plate axial pistons pump, pressure compensated! [6].

A simple design [5] based on a DC motor driving a gear pump, and a hydraulic cylinder can reveal both good enough dynamic performances, and some design

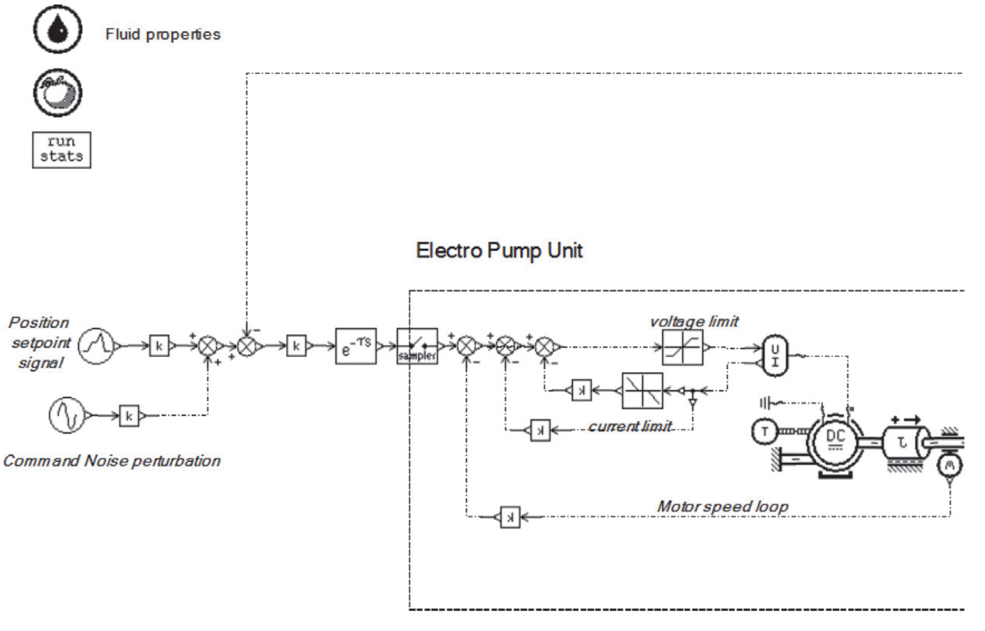


Figure 3.
Electric drive system and the position loop controller.

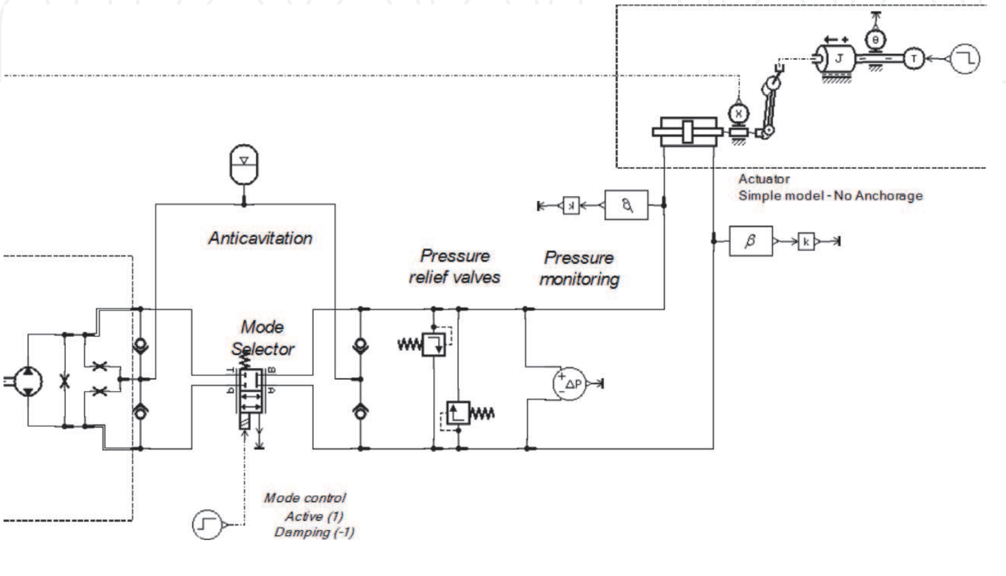
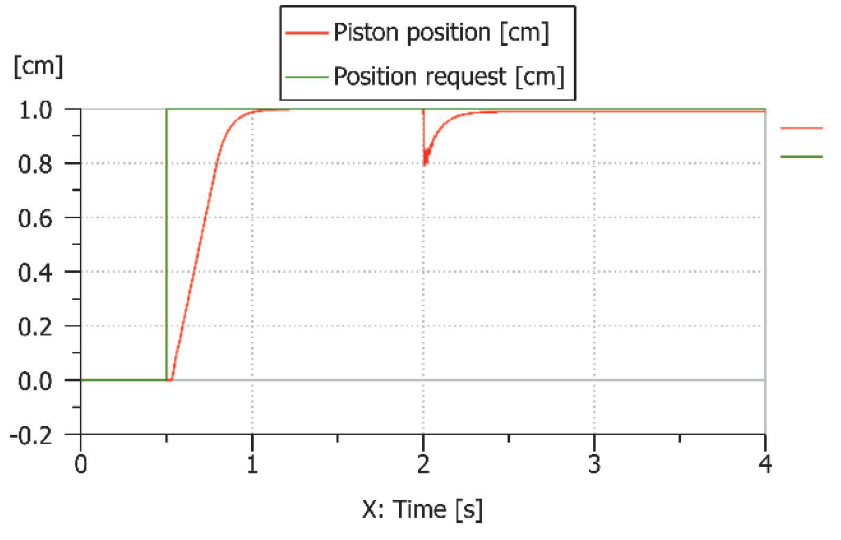


Figure 4.
Hydraulic section of a complete hybrid servomechanism.

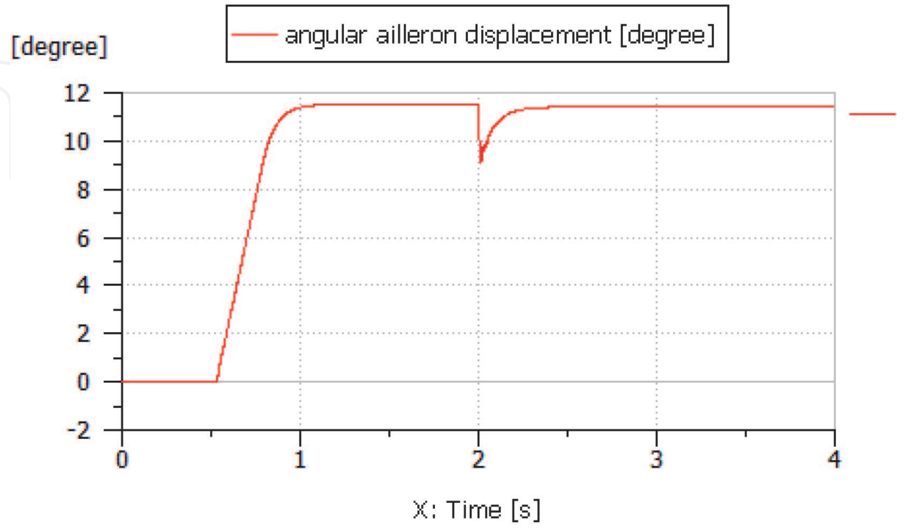
problems involved in the lifetime of a hybrid servomechanism. The time constant can be easy found using a small voltage step input, for obtaining a piston displacement of 1.0 cm from a stroke of 2.5 cm. A reasonable force step input applied on the hydraulic cylinder piston rod can show the system capability to reject common disturbances. Both events were simulated with Simcenter Amesim language for a pump of 1 cc3/rev, reaching 9000 rev/min and 250 bar, driven by a small DC motor of 25 Nm at 270 V and 45 A, with shaft speed sensors used to allow the speed control. The results are presented on the same diagram from **Figure 5**. The time constant of the electro pump is less than 0.25 s, and the piston final position is reached in less than 0.7 s. A piston sudden load variation of 40,000 N generates a drift of about 20% from the nominal value 0f about 80,000N.

Figures 6–8 show the evolution of the main parameters of the pump during the studied transient.

A sudden aerodynamic load on the aileron can generate a short cavitation period in the suction line of the pump. This dangerous event is avoided by loading the



a)



b)

Figure 5.
Dynamic response for a common position request followed by the rejection of a sudden aerodynamic load: (a) Position request and the piston sliding position; (b) Aileron angular position as a function of time.

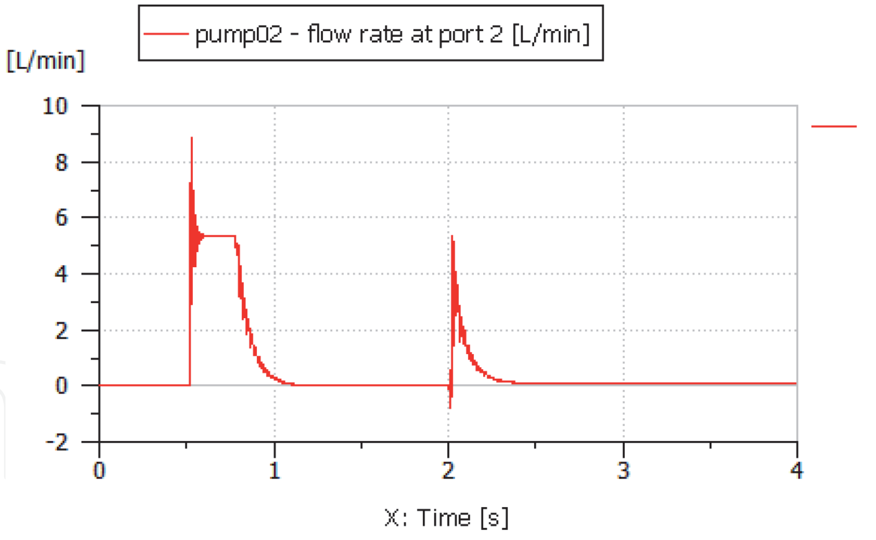


Figure 6.
Pump flow rate evolution during the studied transient.

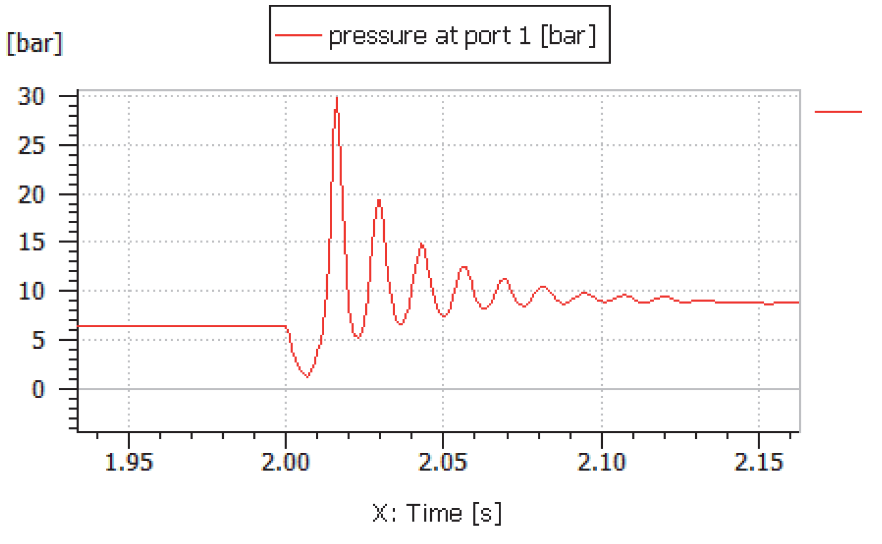


Figure 7.
Pressure in the suction port at the beginning of the aerodynamic load.

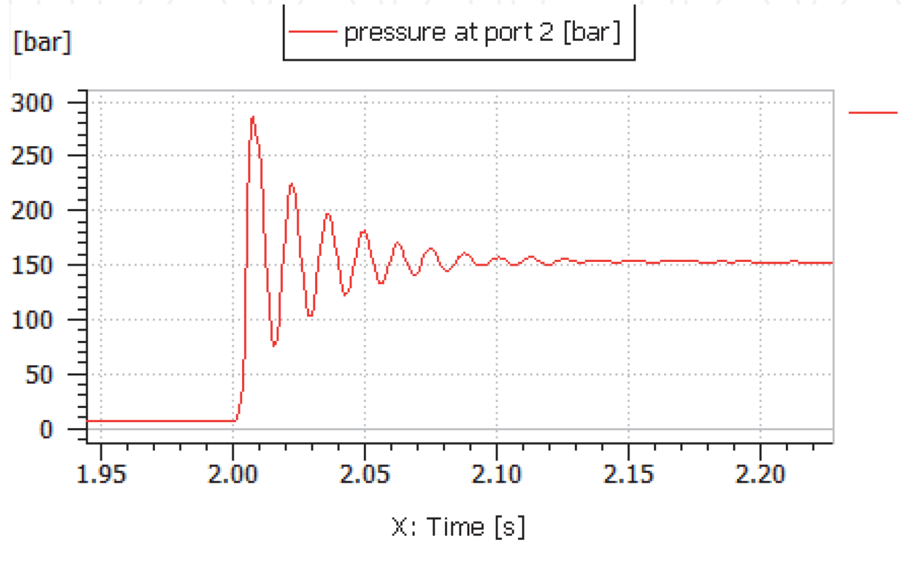


Figure 8.
Pump delivery pressure evolution during the studied load transient.

hydraulic accumulator with nitrogen at 5-6 bar. The compensation of the aerodynamic load applied on the aileron needs a remnant voltage on the armature winding, and a corresponding current (**Figures 9** and **10**). However, the energy needed for the studied operation cycle is very low (less than 120 J).

It is useful to study the frequency response of a basic hybrid servomechanism. This task can easy be accomplished using the "transfer meter" block from the "control library" of Simcenter Amesim (**Figure 11**). A typical result (**Figure 12**) shows a normal behavior for small amplitude input signals: (a) low auto-oscillation risk; (b) lower, but dynamic good enough performance for practice.

The studied dynamic model, even simple, gives an overview of the wide facilities of the behavioral analysis by simulation. However, in reality, some parts of the system should be better considered to get a more predictive representation. Much more, the experimental validation of each new component needs a lot of experimental researches. The history of the high tech electro hydraulic manufacturers has shown a huge effort of fine-tuning and implementing new generations of components and systems [7–9]. Dominque van den Bossche [2] summarized some of developing stages of this process in close connection with the possible dangerous situations, which can occur in any flight control systems. Specific maintenance programs have to be implemented in all manufacturing process related to the automotive engineering.

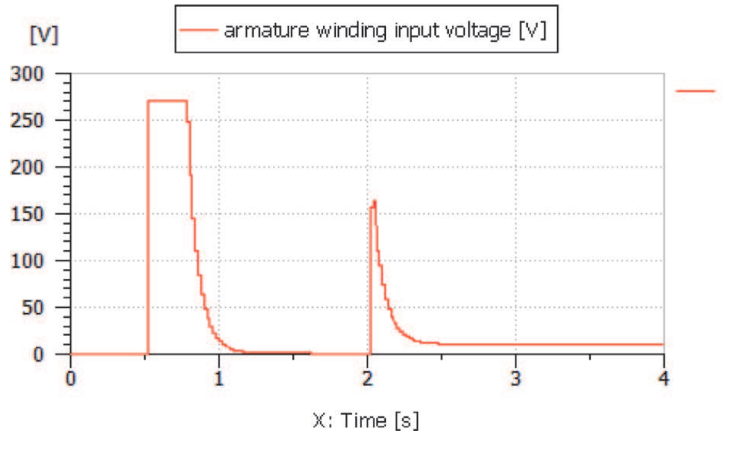


Figure 9.
Variation of the input voltage applied to the armature winding.

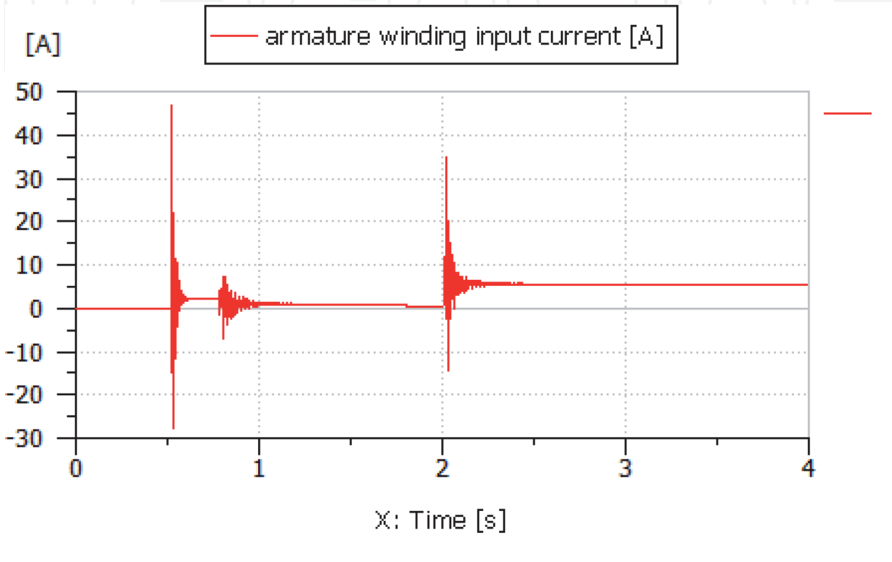


Figure 10.
Variation of the input current in the armature winding.

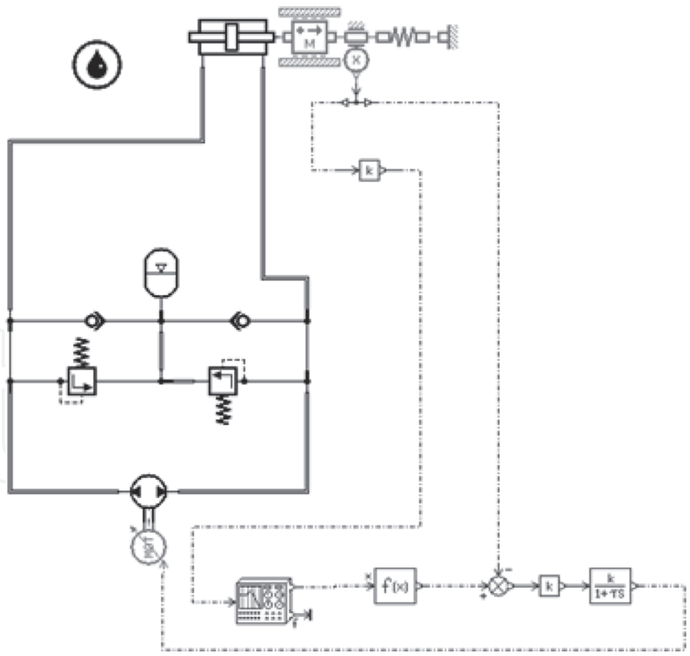


Figure 11.
Simulation network for servomechanism frequency response.

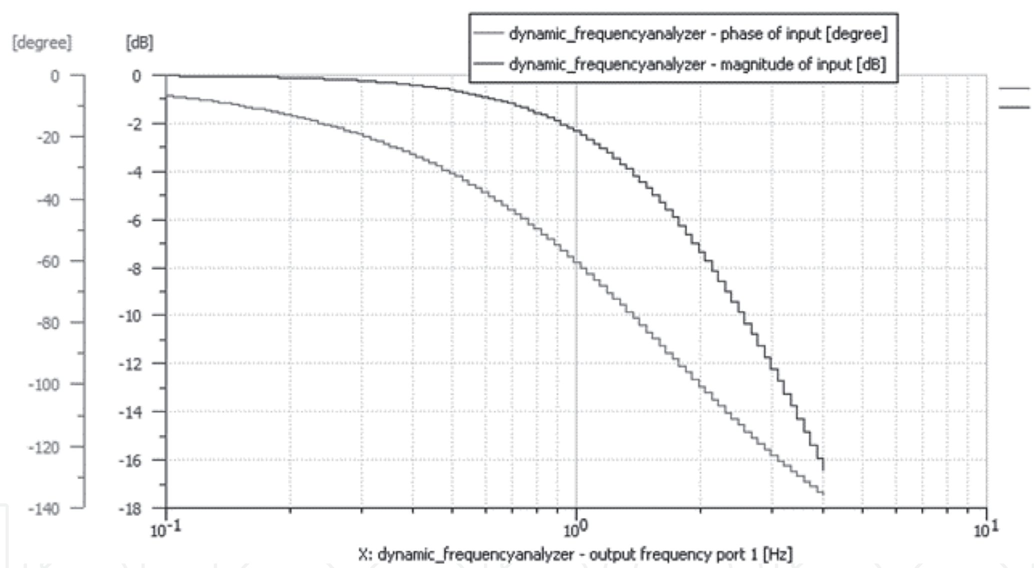


Figure 12.
Frequency response of a symmetric hybrid servomechanism.

The new generation of mechatronic simulation languages reduced drastically this effort. The use of the Real Time Simulation with Hardware In-The-Loop accelerated this process [10–13]. For example, Amesim models can be imported in LabVIEW real time platforms in order to simulate the automotive systems using the general software platform from **Figure 13** [10].

A successful hardware implementation of this concept is presented in **Figure 14**, in order to speed up the design of the new automotive control programs.

The RT simulations with Amesim are frequently used for tailoring different applications of the electrohydraulic hybrid servomechanisms. For example, the complex steering systems of “Self-Propelled Modular Transporter” as that designed by Mammoet [14] need a RTS of all the path followed during the process. The independent propulsion and steering axles are regarded as “super component” in the simulation network of such a complex vehicle. The RTS platform from

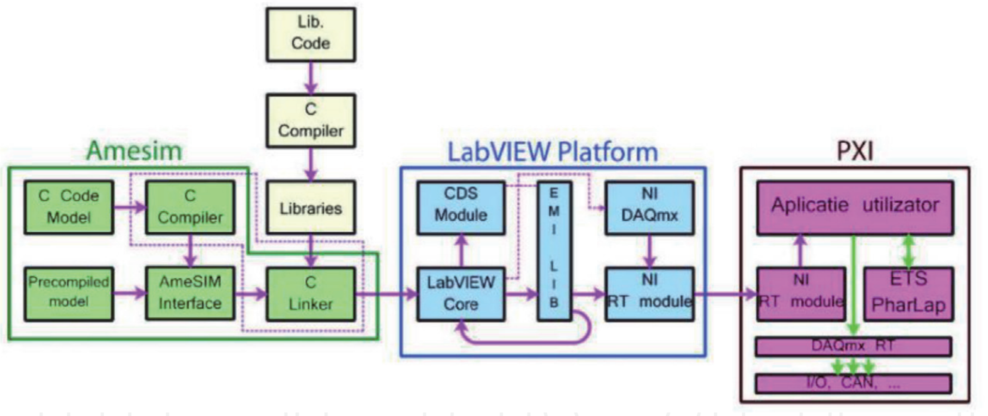


Figure 13.
RTS Platform of Amesim models in LabVIEW RT environment [10]

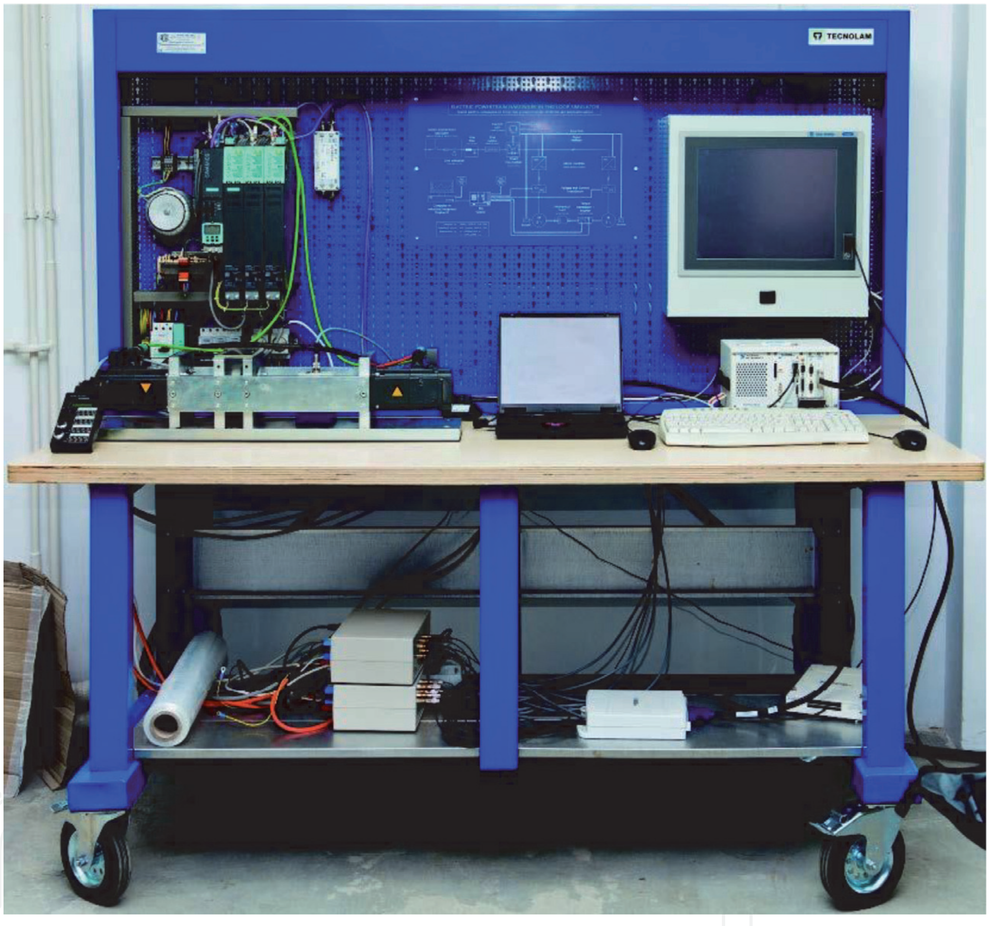


Figure 14.
RTS test platform created in the Fluid Power Laboratory of U.P.B. for automotive electric transmissions [11]

Figure 15, designed by the authors allow the validation of the Amesim simulations for different configurations of complex servomechanisms [12, 13].

3. Hybrid steering servomechanisms for tractors

3.1 Modern trends in autonomous driving systems

A modern trend in the agriculture is about making farming processes more accurate, efficient, and sustainable with advanced satellite navigation systems (like

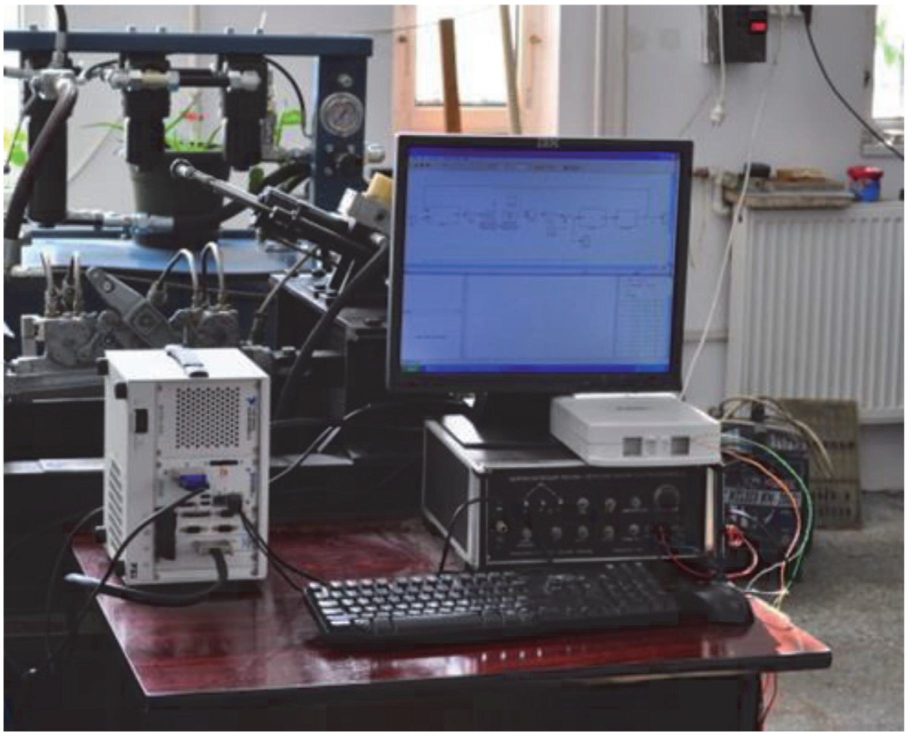


Figure 15.
RTS platform for different complex hybrid servomechanisms.

GPS) and Information Technology (ITC). Precision Farming is raising the agriculture to a new level: doing the right thing, in the right place, the right way, at the right time in the field. Apart from satellite navigation systems, Precision Farming makes use of a number of other key technologies [15, 16]. They include automated steering systems, which take over specific driving tasks like auto - steering, overhead turning, following field edges and overlapping of rows. On tractors, combine harvesters, maize harvesters and other simulate vehicles there is often a need for electrically actuated steering to make automatic GPS controlled steering possible. In addition, manual steering with variable ratio is an often-wanted feature to improve productivity and driver comfort. For this purpose, Sauer-Danfoss [17, 18] has developed a combined steering unit and electro hydraulic steering valve (**Figures 16–18**) named OSPE: OSP for normal manual steering wheel activated

Figure 16.
Hybrid steering module OSPE including both hydromechanical OSP and electrohydraulic proportional servovalve PVE (Sauer Danfoss).

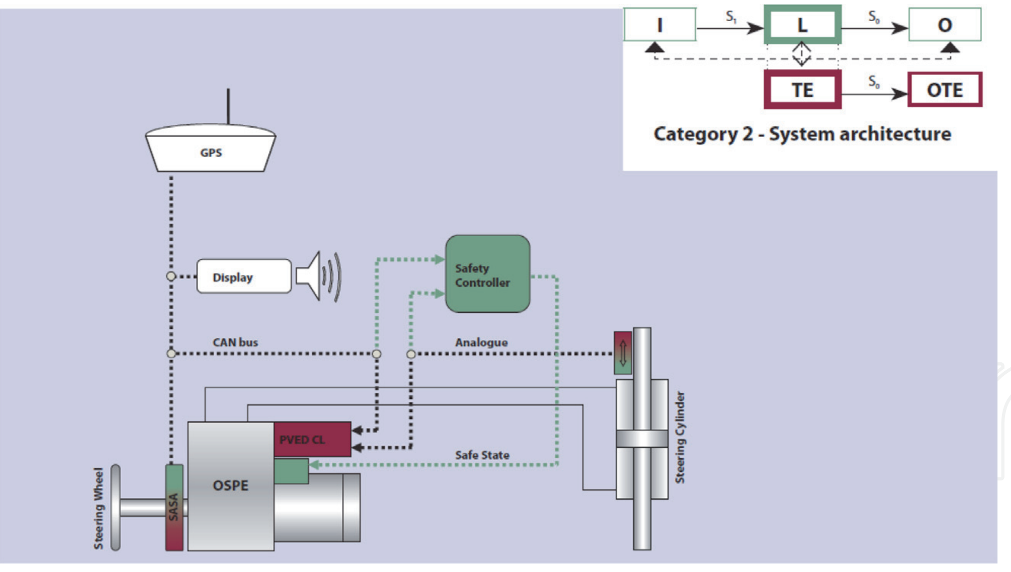


Figure 17.
Hybrid steering system for tractors [17, 18].

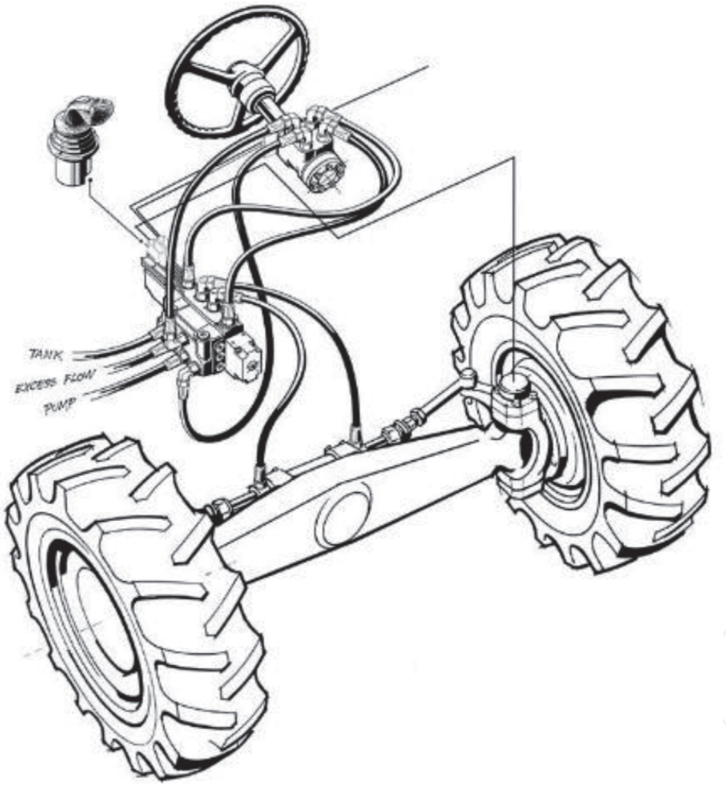


Figure 18.
Electrical and mechanical complex pilot operated steering valve [13].

steering and E for electro hydraulic steering activated by electrical input signal either from GPS or vehicle controller or from steering wheel sensor (SASA) for variable steering ratio. In variable steering mode, the electro hydraulic valve part adds flow to the metered out flow from the steering unit part of the OSPE. This combination has built in safety function in form of cut off valve, which makes unintended steering from Electro hydraulic valve part impossible. So OSPE is the right steering element to build up steering system with very high safety level and so to be able to fulfill legislations demands like e.g. in EU Machinery Directive 2006/42/EC.

Figure 19.
The driving cabin of a modern tractor.

On different kind of heavy mobile equipment, as tractors, mobile cranes, self-propelled modular transporter like Mammoet and dedicated mobile systems like fire trucks there is often need for electrically controlled steering either in the form of a joystick, or fully automatic wireless. For such applications Sauer-Danfoss has developed the pilot operated steering valve type EHPS, which covers a wide range of flows by different geometrical spool flow gain (**Figure 18**).

The above systems turn any tractor in a friendly environment for driver. John Deere [19] gives modern examples of ergonomic cabin of the tractor type 8400R (**Figure 19**).

3.2 Options for a new hybrid steering system

There are some initial decisions to make in order to design a hybrid steering system for any kind of mobile equipment. First, the new system has to allow the human operator to drive himself the equipment anytime i.e. to have the highest priority. Second, the new control system has to be stable and to preserve the accuracy of the previous one under any operation condition. The electrical component strongly depends on the electric power supply, rising real problems from the security point of view. Some electrical power supply systems can reduce the risk of the electrical systems failure. The main problem is to use the same steering cylinders with two kinds of hydraulic metering valves. Both of them need to have close center, or to be isolated upon the request of the driver by an additive directional valve. The relative small fuel consumption introduced by an open center ORBITROL hydraulic steering units can be preserved by driving the input with an electric actuator like a stepping motor with 100-200 pulses/revolution. This option needs a special design of the stepping motor in order to insert it into a steering column. On the other hand, the use of an open center flow valve leads to a poor tracking ability that increases with the steering wheel speed [17]. A typical steady state diagram of such a hydro mechanical feedback steering unit shows a small force capability for high turning speeds. The modern product range has to cover applications of all types of mobile equipment.

This section presents the structure and the performance of a new electro hydraulic steering system for articulated mobile equipment remote controlled. The new concept was designed and tested in the Fluid Power Systems of the University "POLITEHNICA" of Bucharest in order to point out the accuracy and the stability of a control solution based on a dual input (digital and analog) IAC-R REXROTH valve

(**Figure 20**), and a single OBE analog input valve of the same size [20]. The software is individually tailored for the different configurations and combinations of the IAC-R valve by standard parameters set in the factory. Settings for the closed-loop and control parameters are done via the bus interface. Several characteristics define the last generation of electro hydraulic control: fully digitized valve and axis control electronics; position and force control of hydraulic axes directly in the valve; various controller functions available (pressure/flow rate, position and alternating control); input of set points, configuration and diagnosis via field bus (depending on the type via CANopen or Provirus DP). Additional analog set point interface can be used as an alternative to set point input via field bus, but the electromagnetic interferences can create serious troubles, which need safety requirements according ISO 26262.

The CANbus type of controller area network is best suited for multipoint, long range cabling in high electromagnetic interferences areas where analog feedback signals may fail. This new type of control is widely used in military, automotive and aerospace simulating platforms or other systems where accuracy is very important. The behavior of the servovalve in a digital position-closed loop was identified by the aid a special test platform, which includes a strong elastic component, and a variable mass load (**Figures 21** and **22**).

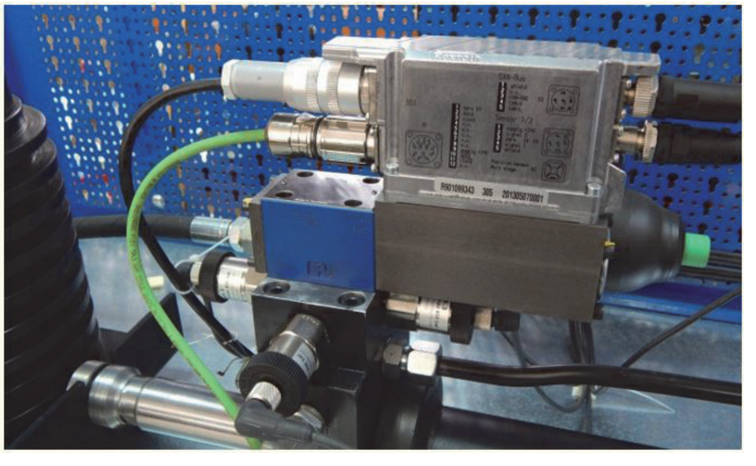


Figure 20.
High-response valve with integrated digital axis controller (IAC-R) and field bus interface (REXROTH)

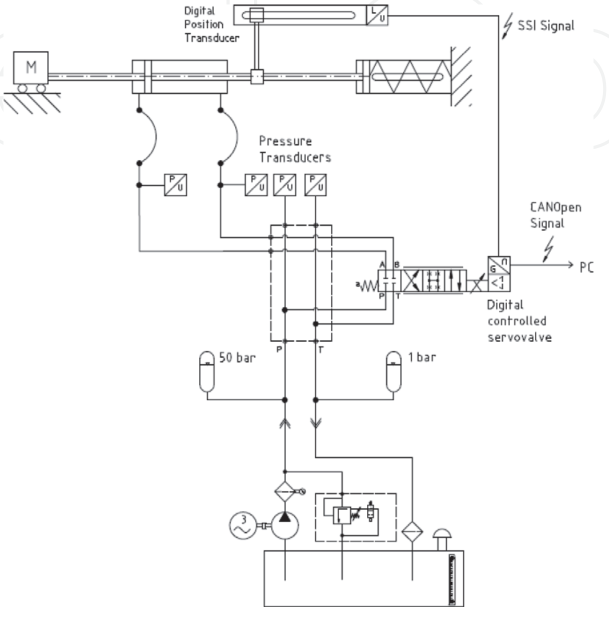


Figure 21.
Hydraulic diagram of the platform for testing digital servovalves.

Figure 22.
Test platform for identifying the digital servovalve performance [17].

A magnetostrictive digital displacement transducer with SSI interface was used for the load. Position reference is set though CANopen bus, and the control algorithm is a PID made with the OBE of the digital servo valve. The reference value for the digital test was generated with the application provided by the manufacturer and sent with a USB<->CANopen adapter. The positioning accuracy depends on the friction force of the steering cylinder as a function of speed (**Figure 23**).

Figure 24 shows a typical response of a servomechanism with P controller. The response time of the digital servovalve is very small: about 2 ms for a 10% input signal. Consequently, the frequency response is very fast (**Figure 25**).

The system performances were identified using a forestry articulated tractor (**Figure 26**) designed as prototype by the research department of the Romanian company "PROMEX" from Brăila [22]. The front chassis was locked, leaving free the back one to rotate on a circular raceway (**Figure 27**). The tractor steering system was studied by the aid of a rotary hydraulic motor controlled in closed loop by a servovalve (**Figure 28**). Then, the steering amplifier was replaced by the servovalve itself.

Usually, the control valve of the ORBITROL hydraulic steering unit is designed with open center for reducing both fuel consumption and steering mechanical

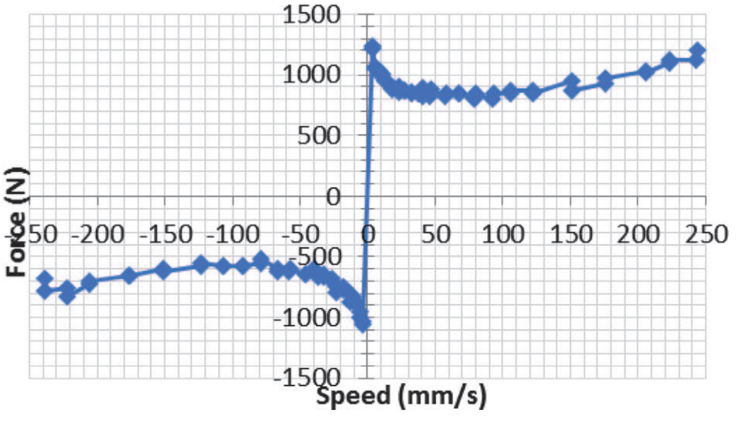


Figure 23.
Friction force of the steering cylinder as a function of speed [21].

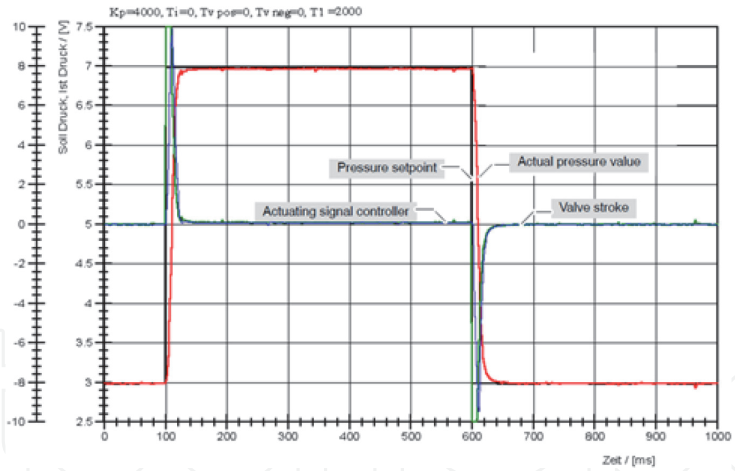


Figure 24.
Typical response of the servomechanism for a P controller with KP = 4.

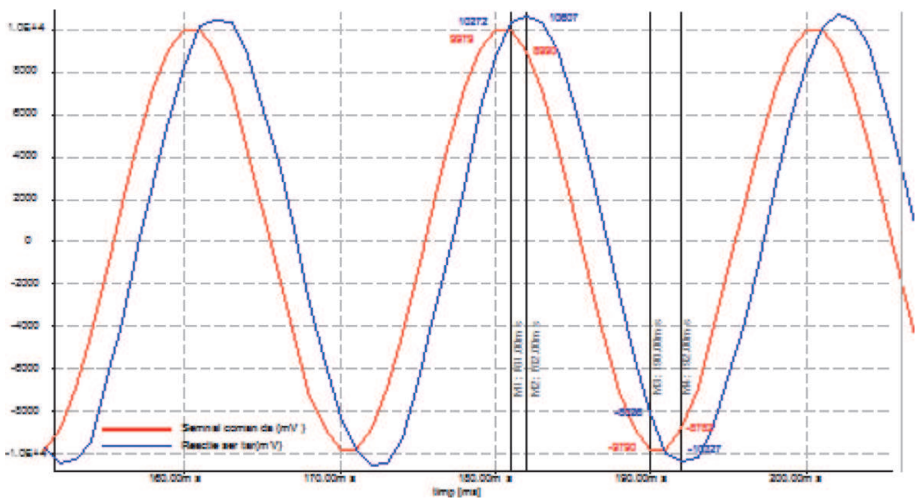


Figure 25.
Frequency response of the servovalve spool position for a sine input of 1.0 V at 50 Hz (given by CANopen).

Figure 26.
Overall view of the articulated full hydraulic tractor.

shocks. The "price" of these gains is a big backlash (**Figures 29** and **30**) which increases with the input frequency [23].

The direct control of the steering angle by a servovalve needs a constant pressure supply but avoids the backlash (**Figures 31** and **32**). However, the hysteresis

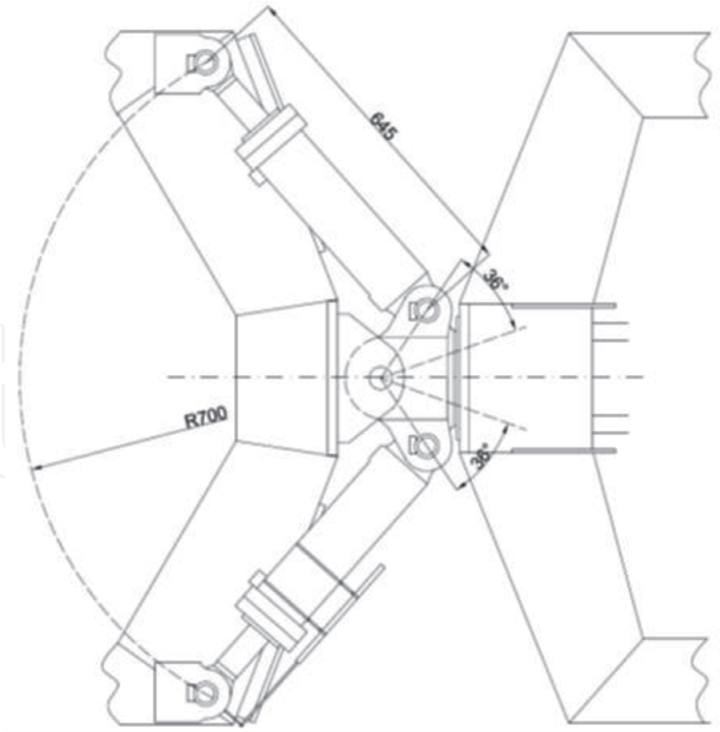


Figure 27.
Plain view of the steering hydraulic cylinders with position transducer.

a) b)

Figure 28.
Hybrid steering servo system driven by an ORBIT motor in close loop: (a) driving system view; (b) rotary feedback potentiometer driven by the motor.

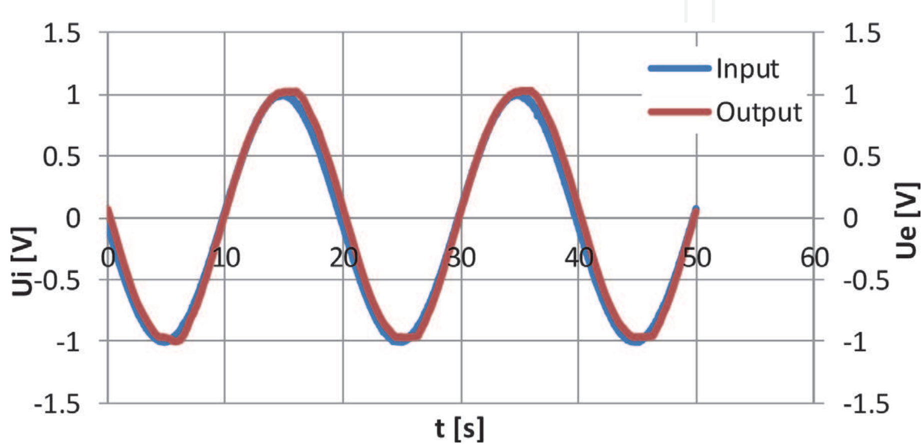


Figure 29.
Steering system response when ORBITROL unit is driven by a hydraulic motor (Ui = 1.0 V; f = 0,05 Hz).

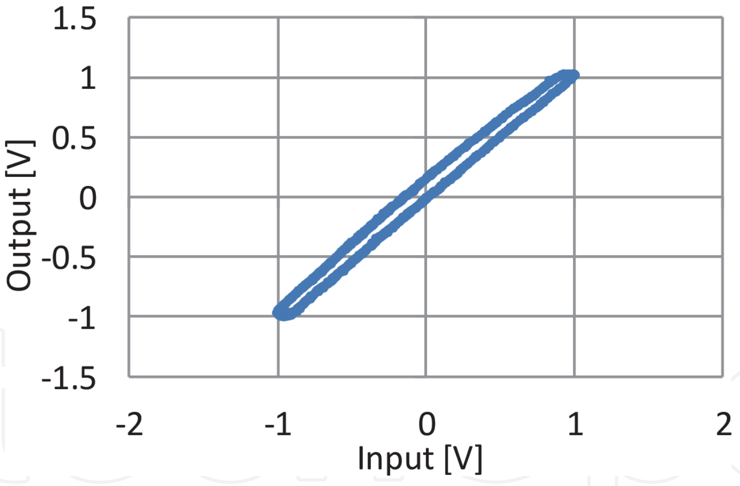


Figure 30.
Steering system steady state characteristics when ORBITROL unit is driven by a hydraulic motor (Ui = 1.0 V; f = 0.05 Hz).

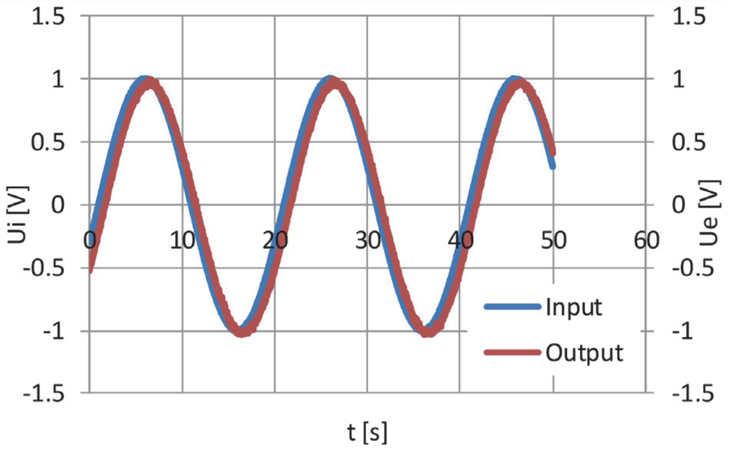


Figure 31.
Steering system frequency response when cylindres are driven by a servovalve (Ui = 1.0 V; f = 0,05 Hz; p_s = 100 bar).

increases with the input frequency. The normal friction forces inside the hydraulic cylinders increase the nonlinearity of the steady state characteristics.

The steering process quality can be improved by increasing the pressure supply, reducing the length of the hoses, and the servovalve gain around the null.

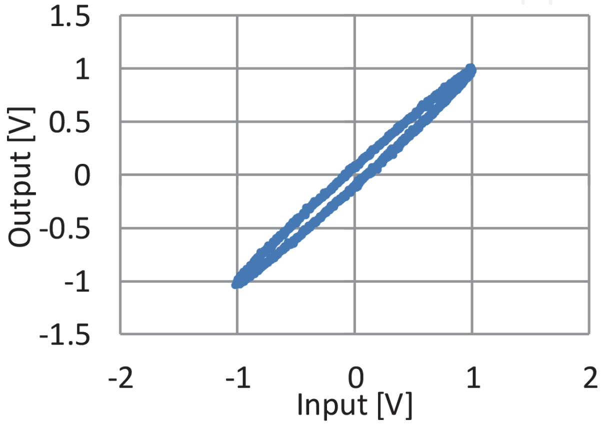


Figure 32.
Steady state characteristics for Ui = 1 V, f = 0.05 Hz and p_s = 100 bar.

A common stepping motor with battery-less multi-turn absolute encoder can be regarded as a possible electromechanical interface in the ORBITROL steering system, but the size and the weight are too large for the normal input torque (about 10 Nm).

4. Hybrid steering systems for trucks and buses

The high-speed trucks and buses offer an important field of applications to the hybrid servo systems. However, the linear mechanical feedback of the classical steering box is still used in modern front axles with independent suspension arms (**Figure 33**) [24].

A hybrid effect can be introduced by a brushless servomotor placed on the steering column, or in a mixing box SC, in series with the torsion bar, under the shape of a module with two inputs, which controls the rotary valve (**Figure 34**).

The rotary valve opening has a high frequency oscillations (**Figure 35a**), but the steering process remains continuous (**Figure 35b**).

The basic rotary steering box of the trucks and buses has the same structure as the linear one, the only difference coming from the feedback: the piston motion is fed back to the torsion bar with a ball screw (**Figure 36**). A brushless motor placed in series with the input shaft can control the motion of the rotary valve (**Figure 37**).

The brushless motor controls the torsion bar by a complex torque and angle sensor composed by Hall sensors and a rotary inductive wheel (**Figure 38**).

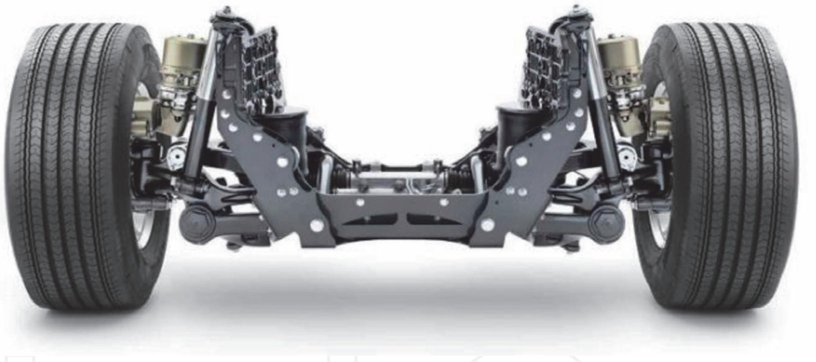


Figure 33.
Front axle of a modern truck with linear steering box.

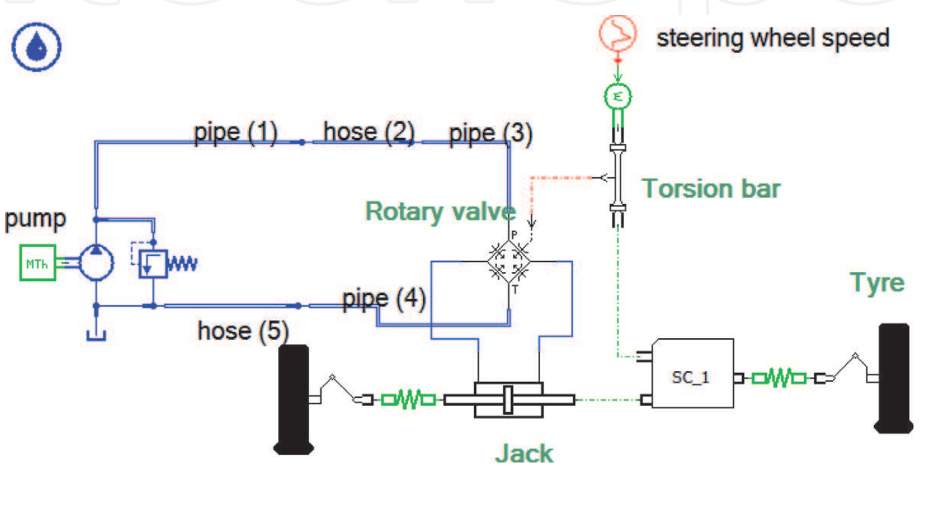


Figure 34.
Simcenter Amesim simulation of a hybrid linear steering box [25].

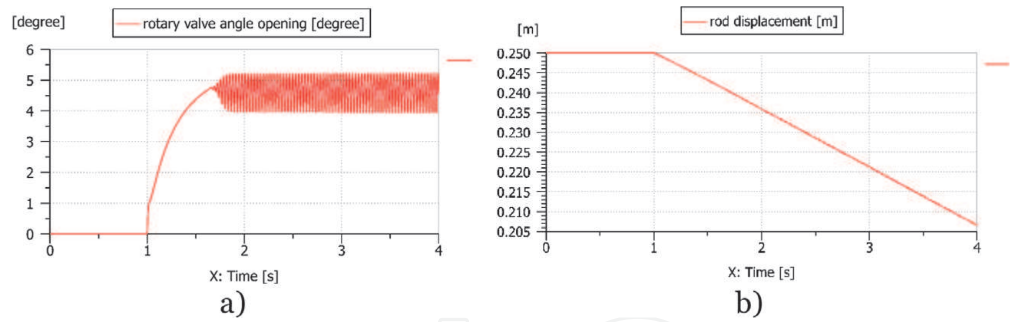


Figure 35.
Valve opening and rod displacement for a hydraulic steering system [4]: (a) rotary valve angle opening [degree]; (b) rod displacement [m].

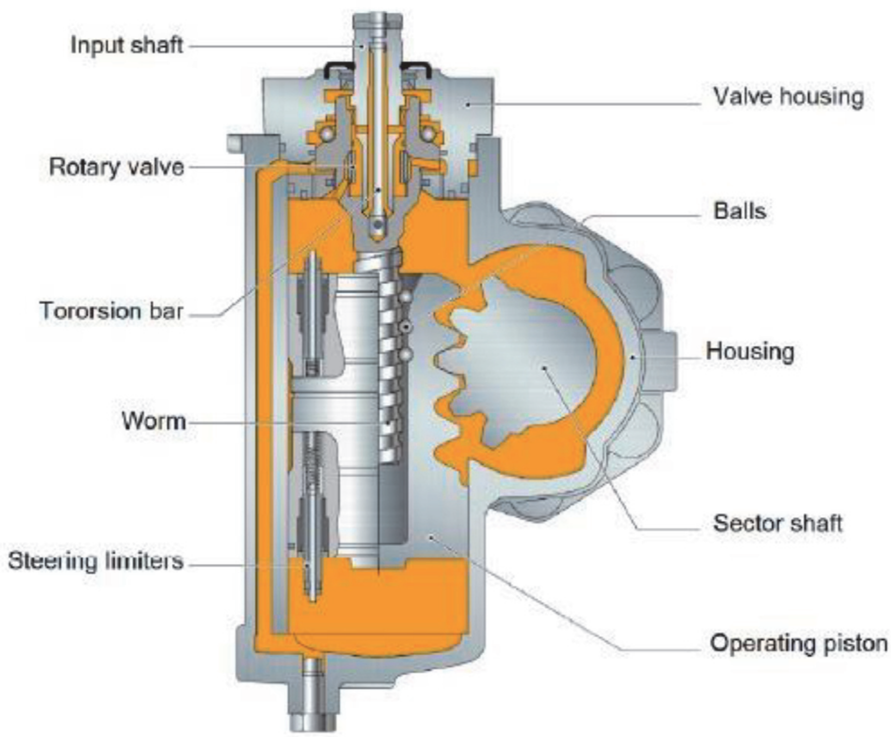


Figure 36.
Steering box with ball screw feedback [22].

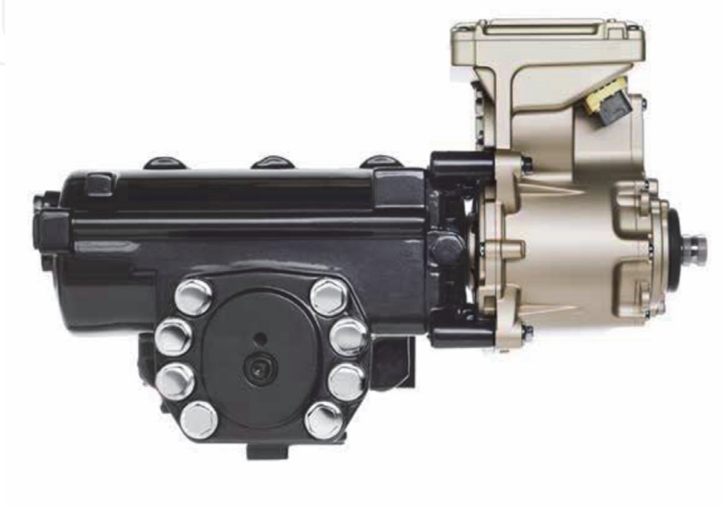


Figure 37.
Hybrid steering box [26].

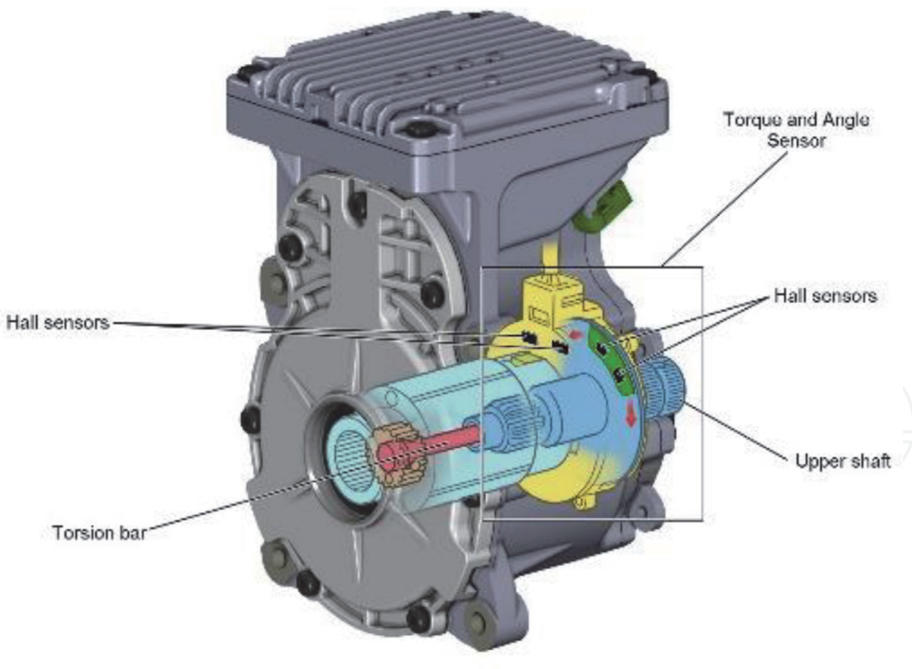


Figure 38.
Brushless motor with complex control functions [26].

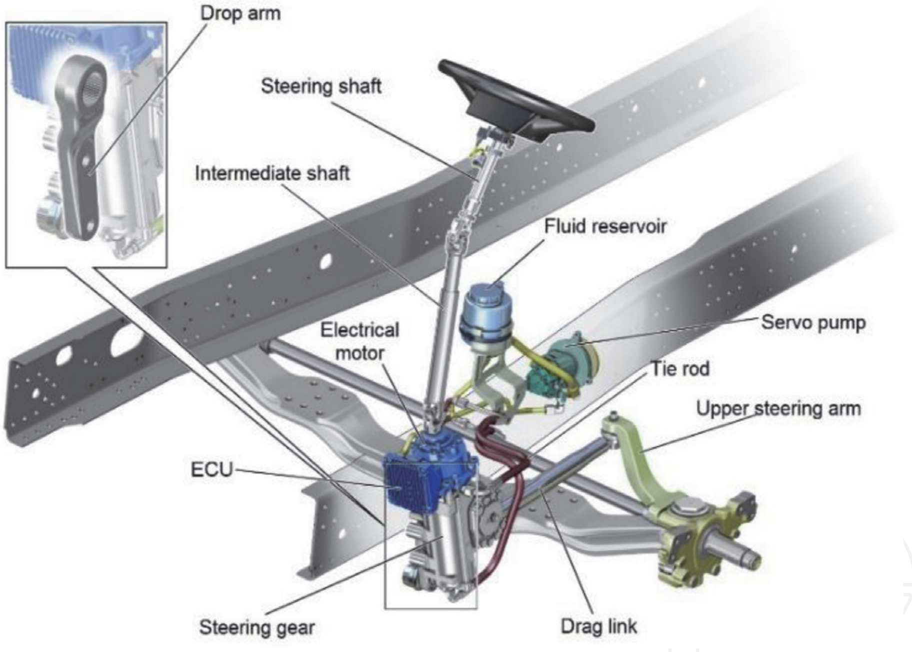


Figure 39.
Components of the hybrid steering system placed in a Volvo truck [26].

A general view of the hybrid system of a Volvo truck shows the minimum changes needed in the standard version of the car for introducing the hybrid feature (**Figure 39**).

The HYDRAPULSE Company from U.S.A. introduced a special kind of hybrid driving system. EHSU is a ruggedized electric hydraulic steering pump (electro-hydraulic) unit with integrated motor, controller, and closed-loop feedback that is specifically designed for mobile steering assist and e-steering applications. The EHSU (**Figure 40**) is available in both high and low voltage models and a variety of pump displacements and power levels. There is no electrical feedback from the steering arm! [27].

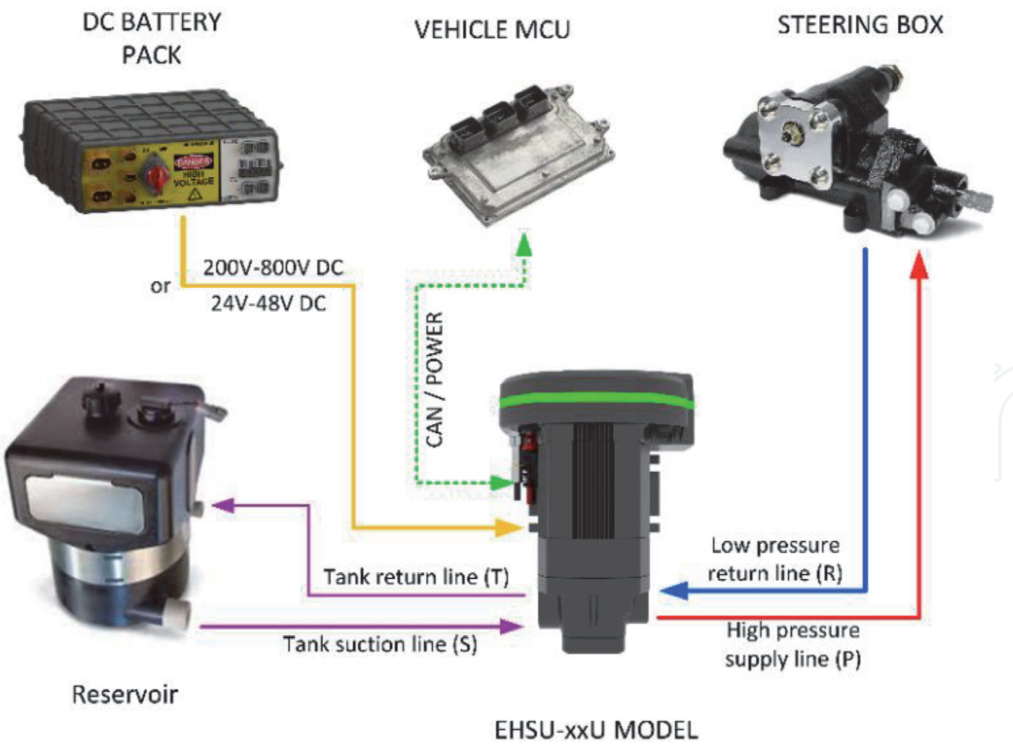


Figure 40.
Electrohydraulic hybrid steering systems without direct feedback.

5. Conclusions and future research

The basic hydrostatic transmission, composed by a volumetric pump and a hydraulic cylinder remains the most simple, compact and light mechanism for generating any force. The combination between a brushless motor, with digital driver, and a ball screw connected in close position loop became already the best driving system for small inertial loads, but the upper limit of the force remains low. The hybrid combination between a brushless motor and a hydrostatic transmission composed mainly by a high-speed pump, and a linear servomotor offers the best performances with the smallest weight and reduced dimensions. In the last decade,

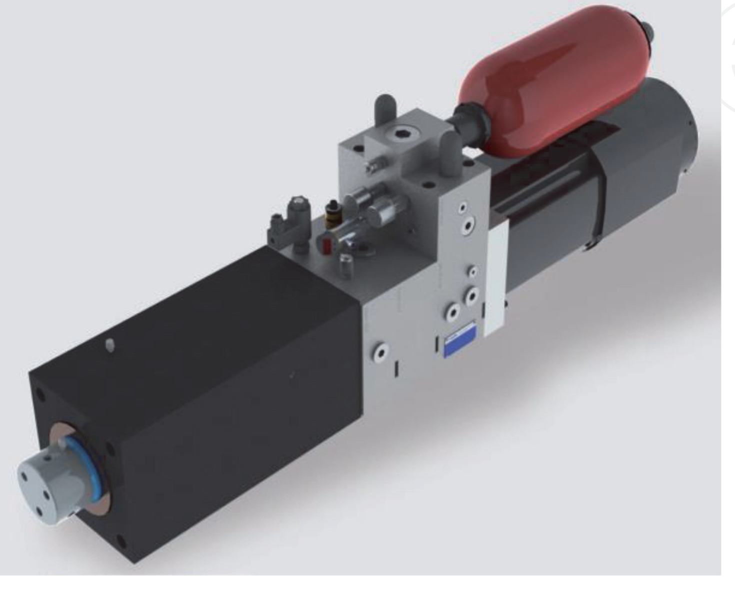


Figure 41.
Voith industrial digital hybrid servomechanism [28].

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a significant progress was achieved in promoting this new generation of compact actuators in all the modern industrial manufacturing process, different kind of steering system for airplanes, ships, trucks, the control systems for engines, turbines, ships, trucks etc. (**Figures 41** and **42**). The author's team created a new type of small power hybrid steering system dedicated to some type of heavy mobile robots. **Figure 43** presents a part of the test platform of the servopump [30]. A FPGA controller was designed for controlling the whole system. The exposure of the experimental results overcomes the frame of this paper.

However, some information about the components of the test bench built in the frame of the University POLITEHNICA of Bucharest can be useful for a better understanding of the design problems. An AC Servo Motor & Driver, MINAS A6 series produced in 2016 by Panasonic Corporation Motor Business Division was chosen for driving a reversible high-pressure gear pump XR012 from Vivolo Corporation.

A PXI industrial device from NI Corporation [20] controls the assembly by the aid of the LabVIEW real time environment. The hydraulic cylinder, designed by the authors for high mechanical efficiency, includes a tension and compression load cell Model 2712 – 500 from Sensy Company from Belgium; two pressure sensors type 7768202 from VIKA Company, and a linear displacement transducer type MLS130-200-R-N from Penny & Giles Company. Hydac Group and Bosch Rexroth Group supplied the hydraulic circuit components. After the first series of performance test, a cheaper dedicated controller was designed, and successfully tuned (**Figure 44**).

Figure 42.
Rexroth industrial digital hybrid servomechanism [29].

Figure 43.
Servopump for hybrid servomechanisms designed in the Fluid Power Systems Laboratory of U.P.B. [30].

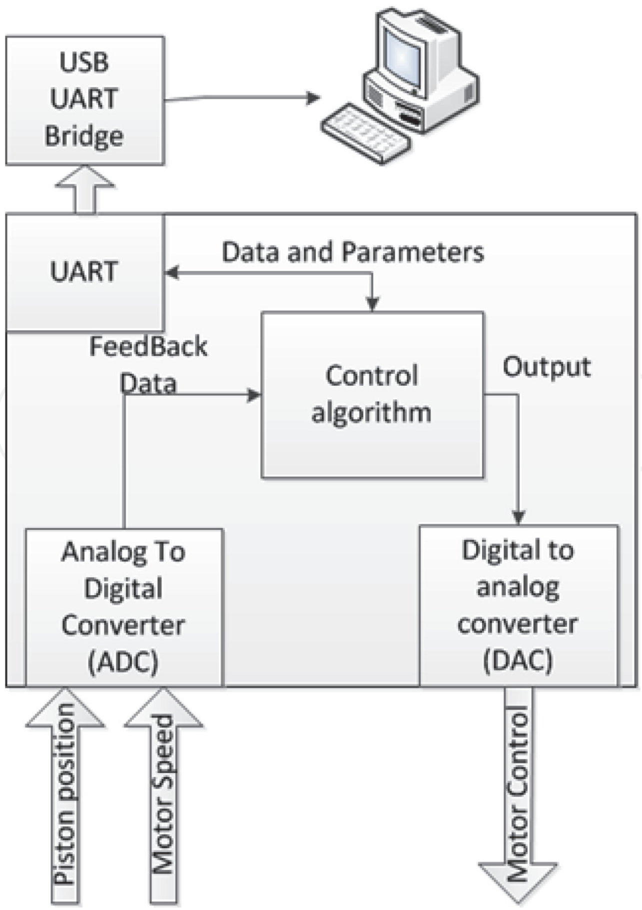

Figure 44.
Architecture of a configurable embedded controller for hybrid automotive servomechanisms [30].

Anyway, the road to a mature industrial design will be a long one, and according to Dirk Hartmann and Herman Van der Auweraer from Siemens Corporation, it must pass through all the stages of the modern manufacturing process called now Digital Twins [31].

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