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A HIERARCHICAL APPROACH TO AUTOMATION FUNCTIONS

Nicolae PARASCHIV[1]
[1]Automation, Computers and Electronics Department, Prof. PhD Petroleum-Gas University of Ploieşti, Romania, Bd. Bucuresti No. 39, 100680 Ploiesti – Romania, nparaschiv@upg-ploiesti.ro

Abstract: *Process control can be done either automatically or manually in order to achieve the objectives of quality, efficiency and security. The automatic approach consists in totally or partially implementing the monitoring, control, safety and optimization functions. This paper presents a hierarchical approach to the four fundamental functions of process automation along with formalization elements of two-level hierarchical systems. Hierarchical organization along with distributed approach on one or more levels increases the ability for data processing in real-time and creates the premises of advanced automatic control implementation. The hierarchical approach to the control of a vessel on a navigable river is presented as a case study.*
Keywords*: process objectives, process automation functions, hierarchical and distributed systems, real time, vessel's input and output variables.*

The hierarchical approach to process automation

A process is a sequence of transformations in space and time associated with objects or phenomena. Depending on its utility, a process has targets of quality, efficiencyand security [7]. The process is driven in order to achieve these targets, by applying of required commands.

The targets are strongly related to the reference state of the process, whereas the outcome of the process is related to its current state. If the intervention in system is made after occurrence of a difference between its current state and its reference state, the control is corrective and is often referred to as feedback control. If the intervention in system is made after a modification of some disturbances, the control is preventive and is often referred to as feedforward control.

Corrective control is aimed at error elimination, while preventive one is aimed at error prevention. The main advantage of feedback control consists in the possibility of canceling the error regardless of its cause. One of the disadvantages of feedback control is the fact that the time necessary for error elimination depends on process inertia. During error elimination, the process is in transient regime. A major target of feedback control implementation is the reduction of the transitory regime duration. One of the ways to achieve this, is a hierarchical organization of system.

Hierarchy is the functional division of a control system in hierarchical levels, the sampling intervals [10] increasing from the base to the top of the hierarchy. If simultaneous processing takes place within one of the levels, then it will be distributed. According to [5], the following hierarchical systems can be identified: multilayer, multilevel and multi-echelon.

An expression of multi-echelon structure is Distributed Control Systems (DCS). Figure 1 shows a two-level DCS, where the first level is distributed.

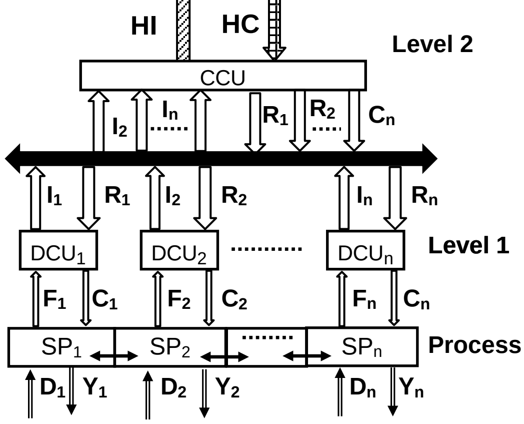

Fig. 1. The structure of a hierarhical control system.

In figure 1 the process is divided into the following subprocesses: SP_1, $SP_2 \dots SP_n$. SubprocessSP_i,which includes the transducer (sensor) and the final control element for each controlled variable, has the following inputs: the sets of disturbances *Di* andcommandsignals C_i. As far as its outputs are concerned,subprocess SP_icontains the sets of controlled variables Y_i and feedback signals F_i.It should be noted that subprocesses may interact.

As previously mentioned, the first level is distributed. It contains DistributedControlUnitsDCU_1, $DCU_2 \dots DCU_n$. DistributedControlUnit DCU_i corresponding to subprocessSP_i. Each DCU_i has the following inputs: the sets of feedback signals $F_i$and references R_i. The outputs of DCU_i arethe sets of command signals C_i and feedback informationI_i for the second level.

At the second level, there is the CentralizedControlUnit (CCU)which coordinates the distributed units from level 1. The inputs of CCUare represented by sets of feedback informationI_i from level 1 and coordination information *HC* froma potentialhigher level. As regards its outputs, they are: information *HI* toapotentiallyhigher level and references R_1, $R_2 \dots R_n$.

The evolution of subprocessSP_ican be described via the function below:

$$S_i : D_i \cup C_i \cup U_i \to F_i \cup Y_i \quad i = 1,2,\cdots,n \ , \tag{1}$$

whereU_i represents the interactions corresponding to subprocessSP_i .The function described via relationship (1) allows the evaluation of outputsF_i and Y_i when interactions$U_i$occur.

The functionality of a DCUfrom level 1 is described via the function

$$T_i : F_i \cup R_i \to C_i \cup I_i \quad i = 1,2,\cdots,n \ , \tag{2}$$

which allows determining of commands $C_i$to subprocessSP_i and of feedback information to CCU.

The following function can be defined for level 2:

$$V_i : HC \cup I_i \to HI \cup R_i \quad i = 1,2,\cdots,n \ . \tag{3}$$

Function (3) is used in order to determine references$R_i$to the distributed unit$DCU_i$and of information feedback to a potential higher level.

A major advantage of the structure shown in figure 1 is the distribution of tasks and implicitly of risks. Under these circumstances, redundancy as a way of increasing operational safety is easier to implement and is therefore cheaper [6]. Also, tasks distribution within the first level facilitates real-time processing, which has beneficial consequences in terms of real-time behavior.

In industry the structure shown in figure 1 is implemented via distributed control systems, such as TDC 3000 (Honeywell®), DeltaV (Emerson Process Management®), Centum VP (Yogokawa®). The references [8,9] contain examples of hierarchical systems design. The structure of SCADA (Supervisory Control and Data Acquisition) systems is similar to the one shown in figure 1. Figure 2 shows a potential DCS architecture [11] .

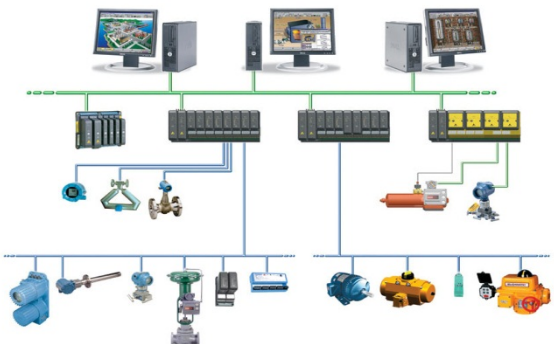

Fig. 2. Example ofDCSarchitecture

DCSoperation is done bymanmachineinterfacesimplemented onthe operator console.Figure 3shows theoperatingconsoleof adistributed systemCentumVP[12].

Fig. 3. The operating consoles of aTDC Centum VP.

The targets of a process without human operator intervention can only be achieved through automation. The author distinguishes the following functions of automation: monitoring, regulation (control), protection, and optimization.

The above functionsare associated withthe followingtypes ofautomated systems:

- Automatic MonitoringSystems (AMS);
- Automatic Regulating Systems (ARS);
- Automatic Protection Systems (APS) ;
- Automatic Optimization Systems (AOS).

In the following sections of the present paper, a hierarchical approach to each category of automatic systems is proposed. The physical integration of automation equipment in hierarchical structures is possible due to their computing and connectivity facilities.

1. The hierarchical approach to automatic monitoring

Monitoring of a process allows the determination of its current state. The evaluation of this state is possible if the values of all the variables of the process are known. If a process is characterized by V variables (parameters) between which exists R independent relationships,

$M = V - R$ variables must be measured. (4)

The minimum number of variables *M* that must be commonly measured according to relationship (4) is known as the number of degrees of freedom [4]. The equations used to obtain the calculated variablesare included in the stationary mathematical model of the process.

The values of measured parameters are provided by remotely automatic measuring systems (RAMS). Figure 4 illustrates the structure of the RAMS, where two major transformations can be identified. The first transformation is performed by the ADC and provides conversion of continuous signal generated by sensor in discrete signal. The second transformation consists in transforming of ADC units into technical measurement units. This transformation occurs in the scaling module SM, which is a software module.

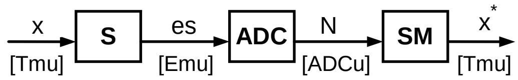

Fig. 4. The structure of a RAMS: S - Sensor; ADC - Analog to Digital Converter; SM - Scaling Module; x - physical parameter; es - electrical signal; N - number of quanta of the ADC; x* - parameter value calculated; Tmu - Technical measurement units; Emu - Electrical measurement units; ADCu -ADCunits.

In figure 4, Tmu represents the measuring unit for parameter x (e.g. temperature - Celsius degrees, speed - m/s). In the same figure, Emurepresents the measuring unit for the electric signal generated by transducer(e.g. V - voltage, mA - current).

As regards the scaling relationship, it depends on the sensor and the characteristic imposed for RAMS. For example, for a linear sensor and a linear characteristic imposed for RAMS, the scaling relationship has the form [6]

$$x^* = a_0 + a_1 \cdot N \,, \qquad (5)$$

wherethe constantsa$_0$anda$_1$depend on the ADC resolutionandfieldsforxandes.

The actual transducers (SMART transmitters) contain the RAMS components described above. The SMART transmitters have advanced a connectivity resource, which allowstheir integration into networks. This feature is shown in figure 2, where the transmitters and the actuators are connected to fieldbus.

The determination of the calculated variables using the measured values is similar to solving a system of compatible algebraic equations where the number of equations is smaller than the number of unknowns [7]. In this approach, according to the relationship (4), the number of equations is the number R and the number of unknowns is the number of variables V.

Given the discussion above, a hierarchical approach to monitoring a processbased on relationship (4) is proposed. Figure 5 shows the proposed hierarchical structure.

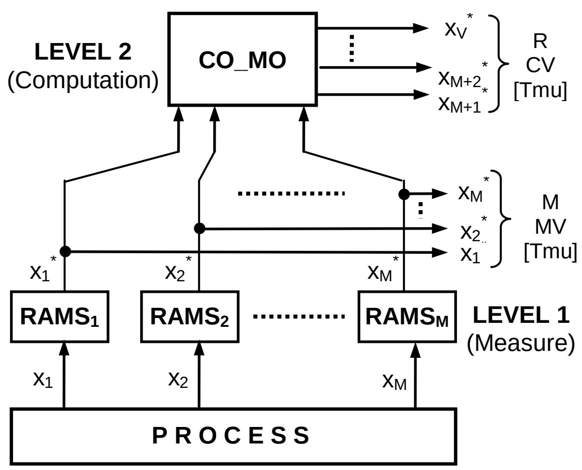

Fig. 5. Hierarchical monitoring structure: RAMS- Remotely Automatic Measuring Systems; CO_MO- Computation Module; CV-Computed Values; MV- Measured Values; Tmu - Technical measurement units.

The hierarchical monitoring structure shown in figure 5 contains measurement systems at level 1. This level provides level 2 with the values x_1^*, x_2^*, ... ,x_M^* for M measured parameters. The computationmodule(CO_MO)at level 2determines thevaluesforR parameters,based on R equationsand onmeasured valuesforMparameters.

The hierarchical approach to automatic regulating

A process is regulated (controlled) if it can be brought and kept into a reference state. This reference is reached and maintained through modification of the commands. If the human operator no intervenes to modify the commands, the regulation (control) is automatic.

Depending on their structure and tasks, the Automatic Regulating Systems (ARS) may be conventional or advanced.

The ARS with conventional structureare associated with maintaining reference for a single parameter. Its action may be either corrective (delayed) or preventive (anticipatory).

The corrective action implies modification of the command when a difference occurs between reference and controlled variable (regulated). This difference is commonly known as an error, and ARS acts after the error or its effect has occurred. The main advantage of a feedback regulating system is the elimination of the error, regardless of its cause. Another major advantage consists in the use of universal algorithms to determine command. PID (Proportional-Integral-Derivative) is such an algorithm which is described via the relationship below:

$$c = c_0 + K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) \cdot d\tau + T_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \right], \qquad (6)$$

where: c is the current command;
c_0 – error-free command;
e – error;
K_P, T_i, T_d – tuning parameters.

According to the relationship (6), the command is determined using the following types of errors: the current error (proportional term), the accumulated error (integral term) and anticipated error (derivative term).

If the command's modification is done when one or more disturbances vary, the action is preventive (anticipatory). Its aim is error prevention (in the sense mentioned above), and its main advantage is maintaining the of the reference value of the regulated variable when disturbances occur. Preventive action implies the command determination using certain algorithms required by the characteristics of the process.

The running of a conventional ARS requires measurement, command and execution functions performed by sensors, regulators and actuators, respectively. The process is included in the fixed part, along with the sensor(s) and the actuator(s). The regulator represents the variable part of an ARS. This feature is explained by the possibility of influencing the regulator's performances by tuning.

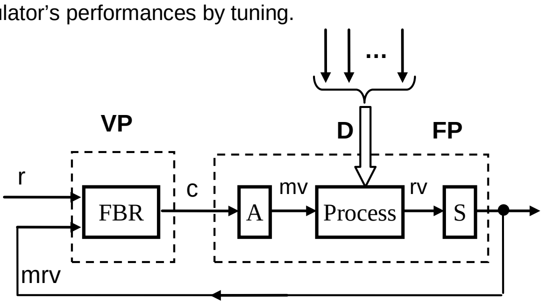

Fig. 6. Feedback loop structure: FP-Fixed Part; VP-Variable Part; FBR-FeedBack Regulator; A-Actuator; S-Sensor; r-reference; c-command; mv-manipulated variable; rv-regulated variable; mrv-measured regulated variable; D-Disturbances.

Figure 6 shows the block scheme of an ARS with delayed action (corrective). As it can be seen, there is feedback from the regulated variable (the effect) to the regulator. This connection allows the elimination of the error (the correction) without any knowledge of its cause(s) being required.

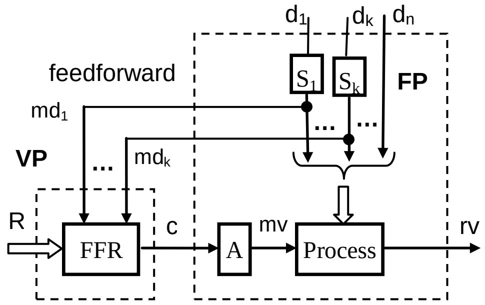

Fig. 7. Feedforward system structure: FP-Fixed Part; VP-Variable Part; FFR-FeedForward Regulator; A-Actuator; S_1…S_k-Sensors; R-reference vector; c-command; mv-manipulated variable; rv-regulated variable; d_1…d_k- considered disturbances; md_1…md_k-measured disturbances

Figure 7 shows a block scheme of an ARS with anticipatory action (preventive). As it can be seen, there is feedforward connection from the considered disturbances (causes) to regulator. This connection is aimed at maintaining the regulated variablerv at a constant value when modification of one or more disturbances occurs.

The division of the process into subprocesses allows hierarchy of ARS. The number of levels is equal with number of the number of subprocesses. Two versions of two-level hierarchical ARS will be discussed below.

The first version, shown in figure 8, contains feedback regulators on both levels (LEVEL2 – FBR_2, LEVEL1 – FBR_1).

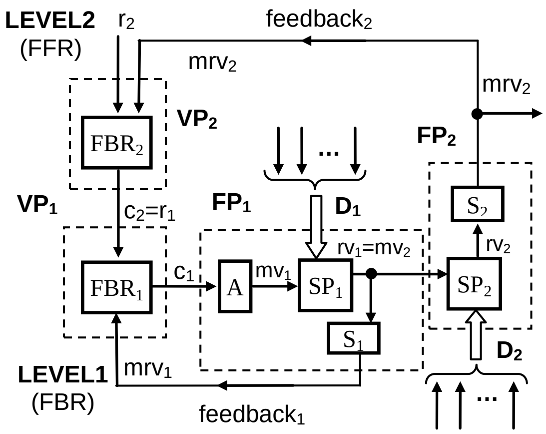

Fig. 8. Hierarchical regulation structure 1: $SP_{1,2}$-Subprocesses; $FP_{1,2}$-Fixed Parts; $VP_{1,2}$-Variable Parts; $FBR_{1,2}$-FeedBack Regulators; A-Actuator; $S_{1,2}$-Sensors; $r_{1,2}$-references; $c_{1,2}$-commands; $mv_{1,2}$-manipulated variables; $rv_{1,2}$-regulated variables; $mrv_{1,2}$-measured regulated variables; $D_{1,2}$-Disturbances.

The structure shown in figure 8 is known as the cascade regulation structure [4]. Loop 1 is the internal loop, and loop 2 is the external one. As far as dynamics is concerned, loop 1 is faster than loop 2.

Feedback regulator FBR_2 on Level 2 is master regulator, and feedback regulator FBR_1 on Level 1 is slave regulator. The command of FBR_2 regulator represents the reference of FBR_1 regulator ($c_2=r_1$). Also, the regulated variable of subprocess 1 represents the manipulated variable of subprocess 2 ($rv_1=mv_2$).

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The second version, from figure 9, contains different types of regulators on the two levels. There is a feedforward regulator (LEVEL2 – FFR_2) on Level 2, and a feedback regulator (LEVEL1 – FBR_1) on Level 1.

Feedforward ARS, from Level 2, is aimed at keeping of the reference value for the output variable rv_2, when the modifications of considered disturbances $d_{2,1} \ldots d_{2,k}$ occurs. Command c_2 of FFR_2 regulator associated with this level is the reference for FBR_1 regulator on level 1(c_2=r_1).

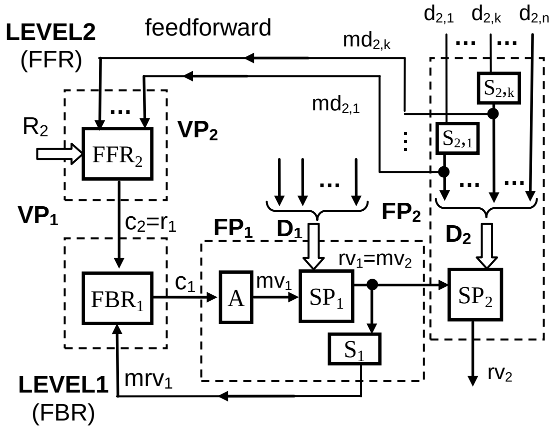

Fig. 9. Hierarchical regulating structure 2: $SP_{1,2}$-Subprocesses; $FP_{1,2}$-Fixed Parts; $VP_{1,2}$-Variable Parts; FBR_1-FeedBack Regulator; FFR_2-FeedForward Regulator; A-Actuator; S_1-Sensor for SP_1;$S_{2,1} \ldots S_{2,k}$-Sensors for considered disturbances $d_{2,1} \ldots d_{2,k}$; r_1-reference for FBR_1 ;R_2-reference vector for FFR_2 ;$c_{1,2}$-commands; $mv_{1,2}$-manipulated variables; $rv_{1,2}$-regulated variables; mrv_1-measured regulated variable rv_1 ; $md_{2\cdot1} \ldots md_{2\cdot k}$-measured considered disturbances; $D_{1,2}$-Disturbances of $SP_{1,2}$; $d_{2\cdot1} \ldots d_{2\cdot k}$- considered disturbances.

The task of ARS feedback, which is hierarchically on level 1, is to establish the reference r_1 for variable rv_1, considering the effect of the disturbances D_1.

In brief, one can say that reference r_1 represents command c_2 for level 2 (c_2=r_1). Also, the regulated variable rv_1 of subprocess SP_1 represents the manipulated variable of subprocess SP_2 (rv_1=mv_2).

2. The hierarchical approach to automatic protecting

The security objective of a process refers ensuring the protection of the human operator and ensuring the environment safety when abnormal situations in the evolution of the process occur.

Automatic protection represents a key component of process automation. Automatic Protection Systems (APS) may have information and/or intervention functions. Information functions are provided by Automatic Warning Systems (AWS), whereas intervention ones are provided by Automatic Blocking Systems (ABS) or Automatic Startup Systems (ASS).

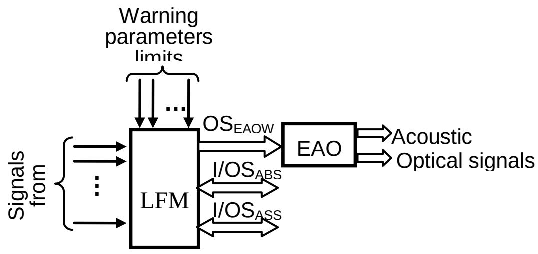

Fig. 10. Automatic Warning System Structure: LFM-Logical Functions Module; EAOW - Elements for Acoustic and Optical Warning; OS_{EAOW}- Output Signals to EAOW; I/OS_{ABS}– Input/Output Signals from/to Automatic Blocking

Automatic Warning Systems (AWS) are open systems. AWSinformsthe operator about theprocess evolution andevents. There are three types of AWS, namely: Confirmation Warning-CW, Prevention Warning-PW, and Trigger Warning-TW.

The CW system informs the operator about the fulfillment of running conditions or status (on-off) of the supervised equipment. The PW system, connected with the Automatic Blocking System, informs that a situation has occured, situation which requiring immediate intervention (correction). If correction is not applied on time, then the ABS system comes into operation. The TW system, which is connected with the Automatic Startup System, transmits the fulfillment of startup conditions to the latter and informs the operator regarding startupoperation success. Figure 10 highlights the AWS structure and its connections.

The Logical Functions Module (LFM) implements logical functions for warning programme [4]. Elements for Acoustic and Optical Warning (EAOW) include lamps, speakers and more. Inputs are the signals from sensors and warning limits for supervised parameters. There are also connections with automatic blocking and startup systems.

Automatic Blocking Systems (ABS) are responsible for turning off an equipment, of a section, or of the whole plant if no action was undertaken after preventive warning. Practically the ABS stops power or raw materials. The ABS is designed to only turn off the equipment/installation, not to turn it on. Because of this feature the ABS is half closed. Figure 11 shows the ABS structure and its connections.

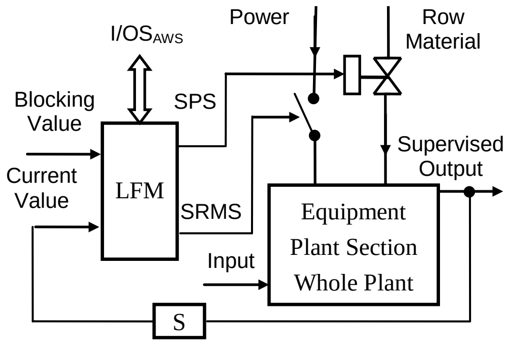

Fig. 11. Automatic Blocking System Structure: LFM-Logical Functions Module; S – Sensor; I/OS_{AWS}– Input/Output Signals from/to Automatic Warning System; SPS – Signal Power Stop; SRMS - Signal Raw Material Stop.

Logical Functions Module (LFM) implements the logical functions for stop sequence. This module generates the signals SPS and SRMS for blocking devices (switches, valves and more).

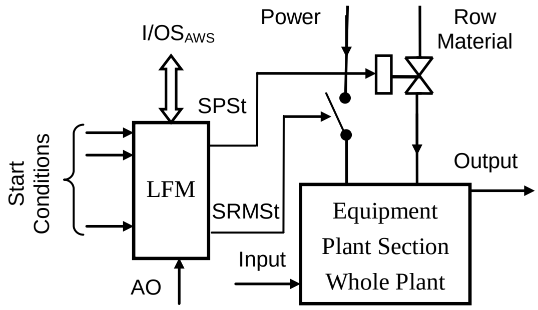

Fig. 12. Automatic Startup System Structure: LFM-Logical Functions Module; I/OS_{ASS}– Input/Output Signals from/to Automatic Warning System; SPSt – Signal Power Start; SRMSt - Signal Raw Material Start; AO – Authorization from the Operator.

The inputs are represented by the blocking value and the current value for the supervised output. Also, the Automatic Blocking System is connected to the Automatic Warning System (AWS). This connection allows signals acquisition from the AWS, and transmission of the blocking signals generated to the AWS. In this manner, the CW section of the AWS informs the operator about the powering off of equipment, of a section of the plant or of the whole plant.

Automatic Startup Systems (ASS) are responsible for the conditioned startup of an equipment, of a section of the plant or of the whole plant. The startup must be authorized by the operator, who performs this operation only after making sure that all the startup conditions in the startup sequence have been observed. This feature makes ASS an open system. An important phase of the startup sequence is represented by connecting energy and raw materials to the sources. Figure 12 highlights the ASS structure and its connections.

The inputs are represented by the startup conditions. Also, the Automatic Startup System is connected to the Automatic Warning System. This connection allows signals acquisition from the AWS, and transmission of the startup signals generated to the AWS. In this manner, the CW section of the AWS informs about of startup operation.

Given the information above, a two-level hierarchical structure is proposed for Automatic Protection Systems. As shown in figure 13, the AWS is placed on the first level of the proposed structure, whereas the ABS and the ASS are placed on the second level.

The two levels interact according to the block schemes in figures 10, 11 and 12. The inputs are represented by limits (warning and blocking), startup conditions and signals from sensors. The outputs are represented by actuating signals (stop/start) to blocking/unblocking elements.

The hierarchical approach to automatic optimization

The efficiency objective of a process is achieved through the optimization. Automatic optimization involves commands application, which minimizes/maximizes a performance criterion (function).

The optimal commands are obtained through optimization problem solving. To define and solve an optimization problem, the following are required: the process model, the objective function, the physical constraints and a solving method.

The objective function commonly includes economic and technical components. By solving the optimization problem values of variables are obtained that minimizes / maximizes the objective function and the minimum / maximum value of the objective function.

If the optimization is integrated into a system of automatic regulating system, the solutions to the optimization problem (optimal commands) can be applied directly to the actuators or may be references for regulators.

Figure 14 shows a proposed hierarchical structure organized on two levels. The first level contains the feedback ARS, whereas the second level contains the optimization. The inputs of the optimization level are: feedback information, economy information and constraints. The outputs of the second level are represented by: references to the feedback regulation and the objective function values.

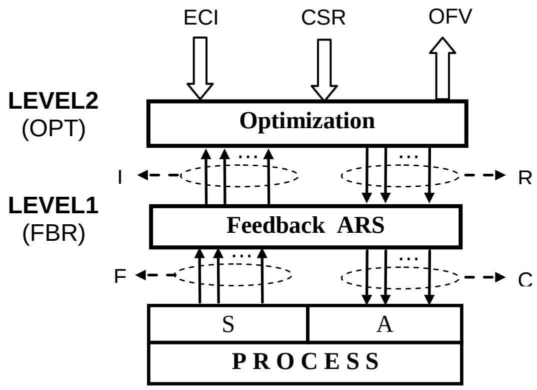

Fig. 14. Hierarchical optimization structure: S – Sensors; A – Actuators; F – Feedback signals; I - Feedback information; R – References; C – Commands; ECI – Economical Information; CSR – Constraints; OVF – Objective Function Value; ARS – Automatic Regulating Systems.

Hierarchical approach to a river vessel's control system

As a regulated process, the displacement of a ship on a river can be characterized by the variables shown in figure 15 [1].

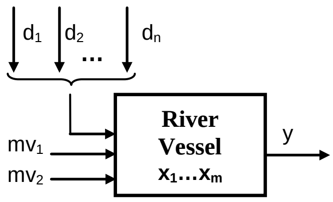

Fig. 15. Block scheme of a river vessel: mv_1, mv_2 – manipulated variables; y – regulated variable; $x_1 \ldots x_m$ – state variables; $d_1 \ldots d_n$ – disturbances.

The regulated (controlled) variable is the current trajectory of river vessel, while rudder angle and engine speed are manipulated variables.

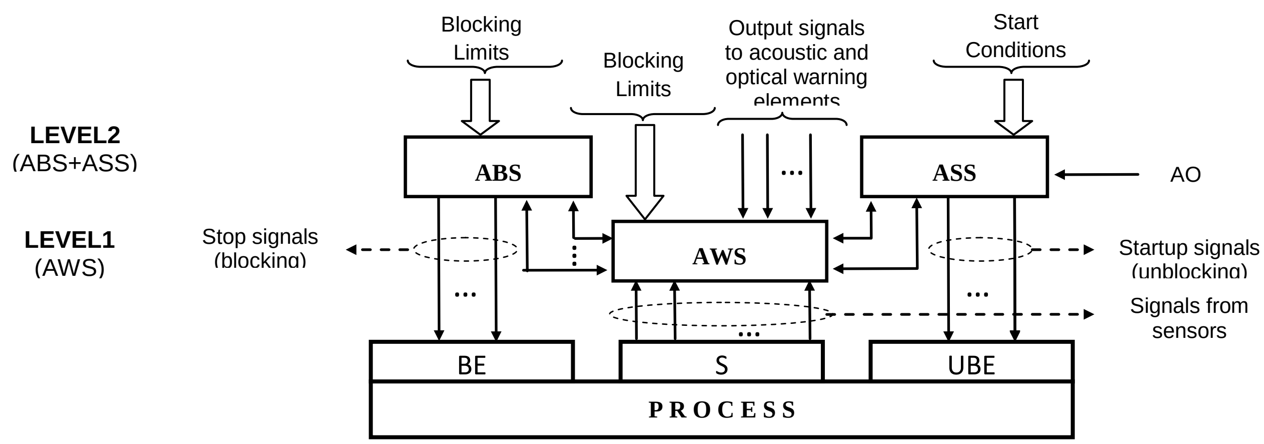

Fig. 13. Hierarchical protecting structure: AWS – Automatic Warning System; ABS – Automatic Blocking System; ASS – Automatic Startup System; BE – Blocking Elements; UBE – Unblocking Elements; S – Sensors; AO – Authorization from the Operator

Regarding the disturbances, these may include: river speed, wind speed and direction, other vessels present on the river and more. The following state variables can be identified: the vessel position in absolute or local coordinates, the vessel's orientation, turning speed of the vessel, the vessel's speed relative to river bank.

The vessel must be piloted so as to achieve the efficiency, quality and security objectives. Piloting involves keeping the vessel on an imposed or chosen trajectory (navigation line). Piloting should be performed in accordance with the rules of navigation and in the river traffic conditions.

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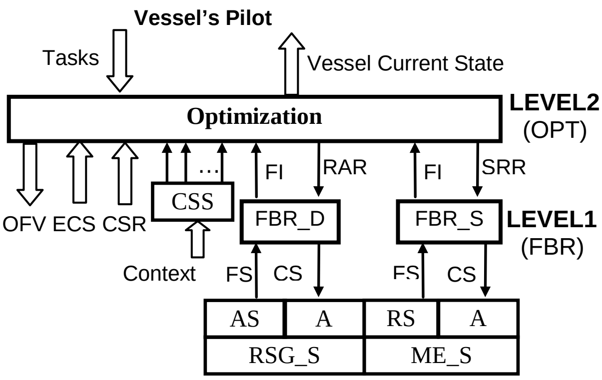

Fig. 16: Hierarchical structure for automatic piloting of a vessel: AS, RS – Angle Sensor; RS - Revolution Speed Sensor; CSS – Complex System of Sensors; A – Actuators; FS – Feedback signals; FI - Feedback information; RAR – Rudder Angle Reference; RSR – Speed of Revolution Reference; CS – Command Signals; ECI – Economical Information; CSR – Constraints; OVF – Objective Function Value.

Figure 16 shows a hierarchical approach to automatic piloting of a river vessel. The approach is according with the informational characterization indicated in figure 15. The process level includes the following subprocesses: rudder and steering gear (RSG_S) as well as the main engine (ME_S). These are considered essential for piloting the vessel [2].

Level 1 is for feedback regulators associated with the vessel's direction (FBR_D) and speed (FBR_S). The outputs of regulators (commands) refer to the rudder angle and speed of revolution of main engine.

Level 2 is the level of optimization. The outputs of this level are references to feedback regulators from level 1. In order to determine these references, the signals from context sensors (CSS) are considered as well. CSS include: vessel radar, laser scanner, stereo cameras, gyroscope, speed sensor, GPS receiver. The electronic chart of the river, the dynamic model of the vessel and the traffic rules are also considered [3]. The pilot supervises the system through a special console. It can obtain information about the navigation parameters and can transmit tasks to level 2.

Conclusions

This paper presents several problems regarding process automation functions in hierarchical approach. It is considered that the hierarchical organization facilitates the automated systems performances.
The first section is a synthesis of the issues, some elements of formalization being also introduced.
In the following sections hierarchical structures of automatic systems are proposed for: monitoring , regulating, protection and optimization. The proposed hierarchical structures for all kinds of automatic systems have two levels.
The last section is dedicated to the presentation of a possible automatic piloting system of an inland vessel.

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