Hybrid Models of Studied Objects Using Remote Laboratories for Teaching Design of Control Systems

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M. Poliakov[1], T.Larionova[1], G. Tabunshchyk[1], A. Parkhomenko[1] and Karsten Henke[2]
[1] Zaporizhzhya National Technical University, Zaporizhzhya, Ukraine
[2] Ilmenau University of Technology, Ilmenau, Germany

***Abstract*—This paper present models of studied objects with the help of remote laboratories containing physical and software components. These hybrid models were described as an integrated system with a hierarchy of controls. The functional structure of hybrid models was formalized using set theory. There are described examples of hybrid models, which software component contains subsystems of virtual models, models of the "hidden" part, the technical state models and environment models of the studied object. There are considered teaching scenarios of hybrid models application. It was given an example of design teaching scenario of diagnostic subsystem of a traffic light.**

***Index Terms*—Hybrid models; integrated system; remote laboratory; set-theoretic model; teaching scenario of learning.**

I. INTRODUCTION

Application field of remote laboratories (RL) [1-5] in the engineering education process is continuously expanding. Along with the subjects that study operation principles and calculation methods of technical devices, it is prospective to use RL in disciplines studying the design principles of these devices and systems based on them, including structure synthesis of these systems. At the same time in the RL for design learning specific teaching scenarios are used. Implementation of these scenarios complicates the structure and increases the complexity of the creation of these laboratories. In papers [6-13] it was considered issues related to functionality, application, diagnostic, added reality of RL models and others.

Absence of typical structural-functional models of studied objects in the known literature complicates its decomposition into subsystems for simplification of the laboratory design process. Therefore, development of the structural-functional models of studied objects presents urgent scientific and technical problem.

II. INTEGRATED SYSTEMS AND STUDIED OBJECT MODELS

Remote laboratories based on the results of scientific-technical revolution obtained in the second half of the twentieth century in a number of scientific and technological areas (listed in Table I).

From such a wide application of scientific advances in RL naturally follows a conception that RL is an integrated system.

The structure of such a system evolves in the implementation of new teaching scenarios. This is particularly evident when using the RL in the learning process of control systems engineering design. The hierarchy of such systems is insufficiently studied and described in the literature, mainly in system-elemental aspect with relationships "whole-part".

In the paper control hierarchy is used for RL description. In concordance with control hierarchy in each subsystem, integrated in system, one defines sets of elements (control objects (CO), control units (CU)) and sets of their relations (mutual and external). In some cases, CU is described by a finite state machine (FSM) model. At the same time CU in the i^{th} hierarchy level subsystem may simultaneously be CO in subsystems of the $(i+1)^{th}$ and higher hierarchy levels. Taken together, these descriptions of all subsystems of the RL integrated system is called the set-theoretic model. More detailed descriptions of these models can be found in [15].

A significant part of RL subsystems presents different models of studied objects . In courses on control systems they are CO and CU models. We consider that studied objects has some functionality F_{SO}, which is inherited in physical (F_{PM}), virtual (F_{VrM}) and visual (F_{ViM1}, F_{ViM2}) RL models. Inheritance structure is shown in Fig. 1.

TABLE I. APPLICATION OF THE SCIENTIFIC-TECHNICAL REVOLUTION RESULTS IN RL

Scientific and technical area	Application in RL
1. Internet, personal computers, distributed systems	Remote real-time access to information resources and multimedia of RL
2. Industrial automation: hardware (microcontrollers, industrial controllers and network, sensors and actuators), software (human-machine interface, emulators, programming environments), specialized automated systems (measurement, control, diagnostics, trainers etc.)	Components of control systems of physical models of study, research and design objects; visual and virtual models of study objects; the structure of software and hardware for design and experiments with physical and virtual models
3. Computer modeling, cybernetics, systems engineering, artificial intelligence, automated design systems	Formal and virtual models of object and control unit top-level
4. Distance learning theory [14]	Learning scenario of RL aids

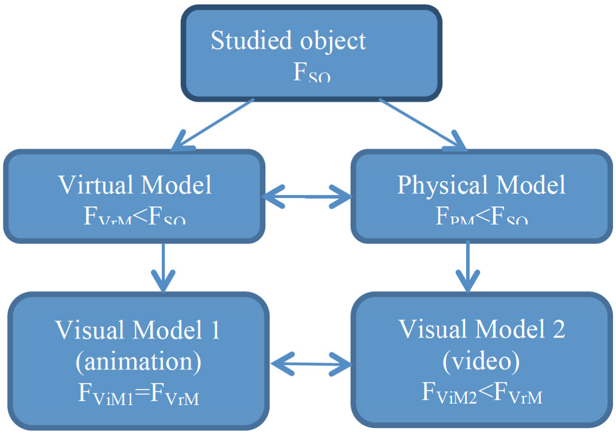

Figure 1. Structure of functionality research of studied object in RL models

The PM of CO contains electromechanics that is similar to the real object, but differs in parameters. Functionality of CO physical model is reduced ($F_{PM} < F_{SO}$) due to the need to meet the requirements of the cost, size and power consumption decreasing. For example, a real elevator has load capacity 500 kg, and a model – 0.5 kg. Parameters of electromechanics differ correspondingly. The functionality of the CU physical model must comply with the functionality of the CO physical model. At the same time the PM of CU may has additional functionality, for instance, associated with the analysis of the student's project (application).

Virtual models include arithmetic and (or) logical expressions describing the behavior of CO as a finite state machine, a logical node, the system with transfer functions and others.

Virtual CO model in known RL has a reduced functionality of CO, corresponding to functionality of a physical CO model. Below we will consider ways to expand the functionality of the virtual model and the sharing of the virtual and physical models (hybrid model).

The visual model presents video of CO or a set of graphic elements on the screen, attributes, location and appearance of which indicate the state and behavior of the physical and (or) virtual model of CO. Only visual models are available for students in the remote browser. An example of a visual model of the tank with liquid – graphical object of the tank outline; the level of the outline fill is proportional to the value corresponding to the program counter in the virtual model. The functionality of visual and virtual models must match each other. Photo- and video image of a physical CO model, obtained with the help of WEB-camera is also a visual model. Combination of visual models of the physical and virtual RL parts forms an image perceived by the student's sensors.

III. Results And Discussion

Based on the introduced definitions let's decompose designed RL into hybrid model, video and control mode subsystems, as shown in Fig. 2.

Video subsystem (DS_2) consists of video monitoring means (CO_2) and control unit (CU_2) of CO_2. CO_2 controls selection of video camera, camera angle and illumination of PM. Despite the fact that the complexity of these devices is comparable or even higher than the complexity of the designed system standard technical solutions are used. Therefore, in this paper the system DS_2 is not detailed.

Hybrid model includes systems: CO physical model (DS_1), four visual (DS_3-DS_6) and four virtual (DS_7-DS_{10}) models.

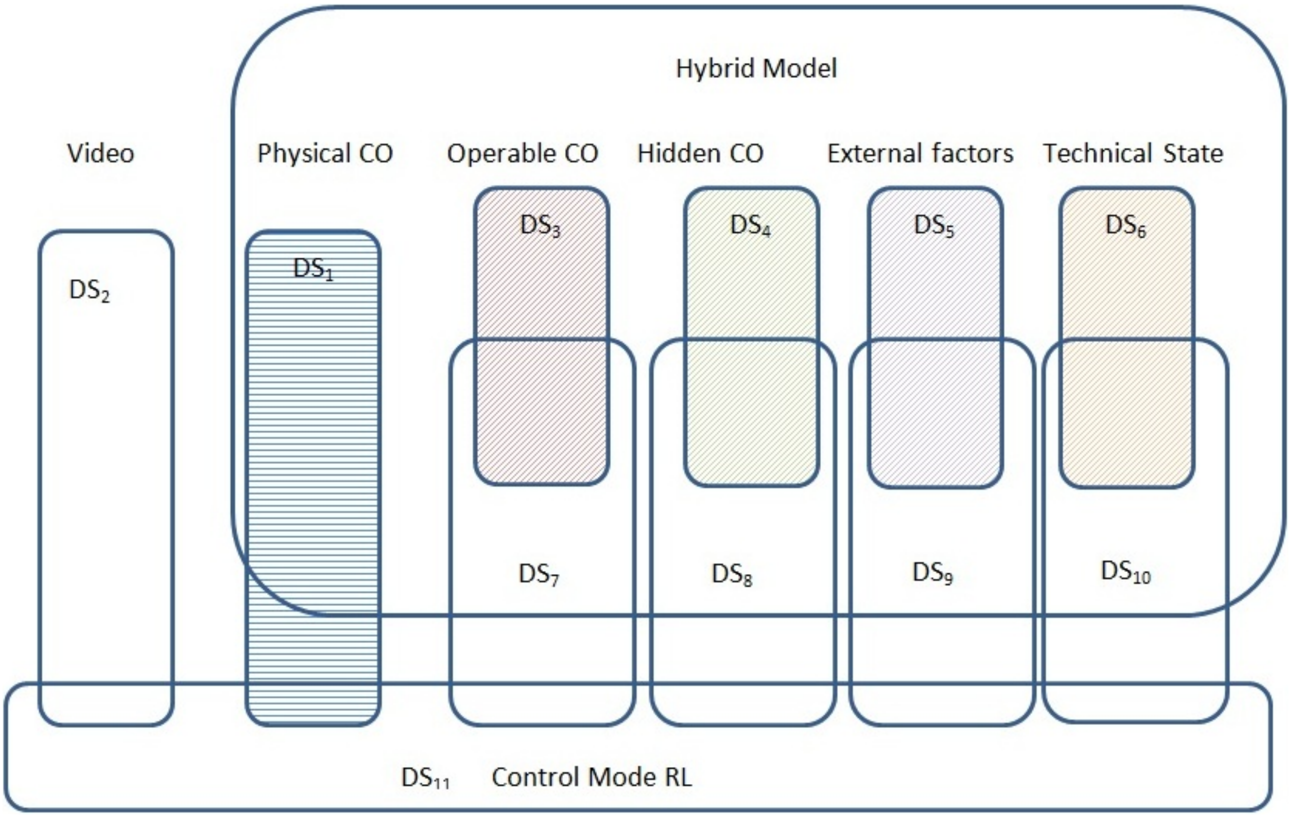

Figure 2. Decomposition of the RL integrated system

System DS_1 includes a control object CO_1 and control unit CU_1. In terms of CU_1, object CO_1 is a set of sensors and actuators. The outputs of the sensors O_{CO1} are inputs of I_{1CU1}, and inputs of I_{CO1} are connected to the outputs O_{1CU1}. As RL is usually operated only in the remote mode, among the CO_1 output signals, buttons and other controls, which are used during operation of the real object, may be absent. Moreover in the electromechanics of model CO_1 there are no elements used in emergency, abnormal operational mode of the real object. They can be modeled in the virtual model of other systems. Electromechanics of a physical model of the designed object is a control object from the RL, but at the same time – control unit from the mechanical part of this object.

The control unit CU_1 processes the information I_{1CU1}, tag of the student control events I_{2CU3} and generates control signals O_{1CU1} by means of physical model CO_1, sensor tags and states of physical model O_{2CU1} for use by other systems.

Visual systems of operable (DS_3) and hidden (DS_4) CO represents one or several graphics screens, each of which corresponds to a particular view of the system being designed, for example, a front view, from the inside, etc. The screens contain video of physical CO or graphical objects and virtual controls of the designed object and the video of a physical model of the object.

Graphical objects match the visible (CO_3) and hidden (CO_4) part of the physical model or studied objects. Graphical objects attributes, such as the coordinates on the screen, the rotation angle, color, width, percent of the figure fill and others change depending on the values of control tags. An example of hidden elements, i.e. the elements that are active in emergency or auxiliary modes of CO operation is a brake of the passenger elevator, which must actuate with the cable break.

In the system DS_3 model CU_3 plays the role of the control unit for the model CO_3. The CU_3 features include the formation of values of the control graphical objects tags, CO_3 in the time function, events of student control, values of sensor tags and states of physical CO model. Block CU_4 generates tag values, depending on the tag values of the actuators of the hidden part of virtual CO.

Visualization model of the external factors DS_5 consist of visual model of the external factors (CO_5) and virtual model of visualization of the CO external factors (CU_5).

Elements of CO_5 present graphical objects, which reflect the current values or the time history (trends) of corresponding tags. For example, the parameters of the power supply, ambient temperature, load current etc. CU_5 elements represent calculation of graphical model of CO external factors dynamics. The inputs of the model are tags of external factors; outputs – control graphical objects tags of CO_5 model and also generated flow of the control events. For example, at analysis of the passenger elevator capacity event flow of the elevator calls can be generated.

Visualization model of CO technical state DS_6 consists of visual model of CO technical state CO_6 and virtual model of CO technical state visualization (CU_6).

If the automaton model is taken as the technical state model, the elements of CO_6 will present graphical objects that visualize the current status of the automaton – its tops and arc. Control graphical objects tags CO_6 are formed by calculation graphical model CU_6, which, in turn, is controlled by tags of CO technical state change.

On the second level of decomposition virtual models DS_3-DS_6 are supplemented with CU and form systems DS_7-DS_{10}. Systems of virtual models DS_7-DS_{10} are formed from control objects CO_7=CU_3, CO_8=CO_4, CO_9=CO_5, CO_{10}=CO_6 and control units CU_7, CU_8, CU_9, CU_{10}.

CU_7 is a control unit of the virtual model of the operable (operated in normal mode) design system. Model CU_7 presents the control automaton that generates tags of actuators of virtual CO based on state tag values of CO physical and visual models, CO control event tags, control tags of modeling modes of the virtual CO. Examples of control tags of modeling modes: scale of model time, synchronization of behavior of physical and virtual models, accounting of the hidden part of the events CO and selection of control events source. The structure of the automaton CU_7 is determined by student with the development and entering of the CO control algorithm description.

CU_8 is a control unit of virtual model of the hidden part of the design system. Model CU_8 presents control automaton similar to the model CU_7.

CU_9 is a control unit of virtual model of the external factors of the design system. Model CU_9 is an automaton which controls scenario of CO external factors changes by forming the tag values of external factors parameters. For example scenarios of changes in CO load and the intensity of it use.

CU_{10} is a control unit of virtual model of the technical state of the design system. Model CU_{10} is the automaton that initiates the events of defects appearing in the CO and adjusts the intensity of their development. For example, the event of parametric failure of the cooling system changes the CO technical state.

Control object CO_{11} of control system of RL modes DS_{11} is logically connects CU of the system DS_1, DS_2, DS_7-DS_{10}. Model CU_{11} is a control unit of RL modes. CU_{11} is the automaton that controls the starting and stopping of automatons belonging to CO_{11}, changes the composition of their states, inputs and outputs, thereby implementing various teaching scenarios of RL application.

With the capabilities of RL hardware and software the occurrence of various RL teaching scenarios is associated. Let’s describe existing and future scenarios in terms of objectives, the initial data, performed tasks, used models and obtained results.

I. Scenario 1. Objective: study of the programming, formalization methods of the control algorithms. Initial data: sensors and actuators of CO, verbal description of the desired behavior of operable CO excluding effects of unobserved variables. Performed tasks: to formalize the CO behavior with the selected method, introduce the formalized description, monitor the implementation and, if necessary, correct the description. Used models: CO_1, CO_3. Example: industrial cell RL the Grid of Online Laboratory Devices Ilmenau (GOLDi) [16].

Scenario 2. Objective: study (to determine the structure and behavior) of CO by monitoring its operation. Initial data: video surveillance at CO model operation according to the reference control algorithm. Performed tasks: determining of the composition of CO sensors and actuators, verbal description of the desired behavior of the operable CO. Used models: CO_1, CO_2. Example: almost all physical models of RL GOLDi.

Scenario 3. Objective: study of CO by remote experiments with CO inputs by students. Initial data: during the experiments the student set necessary for him values of CO inputs. Used models: CO_1, CO_3. Example: elevator of RL GOLDi.

Scenario 4. Objective: to study the completeness of developed by student CO control algorithms using benchmarks of CO inputs changes. Initial data: a benchmark set (BS), i.e., test containing the reference sequences of CO inputs changes, execution of which guarantee student algorithms check. Performed tasks: determining of the composition of CO sensors and actuators, verbal description of the desired behavior of the operating CO. Used models: CO_1-CO_3, CO_5, CO_6. Example: elevator of RL GOLDi.

In the extended scenario version it is provided automatic diagnosis of student algorithms and the formation of a BS subset that reveal the incorrectness or incompleteness of student algorithms. Benchmarks can include inadmissible in normal operating states CO input data sets, leading to an emergency or destruction of CO. In this case, they are executed only on the CO software simulator.

Scenario 5. Objective: to study design methods of control and diagnostic tests of CO and control algorithms. Initial data: verbal description of the standard control algorithm, a list of possible CO faults, a program with the CO control algorithm, a set of uncontrollable inputs (effects of the external environment and internal changes in CO). Performed tasks: development of control and diagnostic tests of CO and control algorithms. Used models: CO_1-CO_6, models of the faults dynamics. Example: elevator of RL GOLDi.

Scenario 6. Objective: design of CO control algorithms, (taking into account the abnormal input actions and possible faults in the CO. Initial data: the same as for Scenario 5. Performed tasks: development of control algorithms based on CO abnormal input actions and possible faults in the CO, evaluation of their performance of the developed algorithms on RL models. Used models: CO_1-CO_{10}. Example: elevator of RL GOLDi.

Scenario 7. Objective: obtaining of CO operator skills. Initial data: CO model with control programs, objectives, control functional, flow of values on the inputs destabilizing the CO operation. Performed tasks: changes in CO monitored inputs during the control algorithm execution to maximize the value of the control functional. Used models: CO_1-CO_{10}. Example: simulator of the vehicle.

Proposed above decomposition principles of the integrated RL into systems let's consider in the example of the "elevator" model of GOLDi laboratory, which image is shown in Fig. 3.

Structure of physical (model CO_1) and visual (model CO_3) CO model is shown in Table II and III respectively.

Referencing of elements of CO_1 model to physical model variables is presented on RL GOLDi site.

Elements of the visual model CO_3 consist of graphical objects, some of which has animated control by the tags of virtual model CO_7. So graphical objects "Cabin" which is grouped with graphical objects "Door" has control "vertical position". Graphical objects "Lamp of Cabin State" has control "color" from the variable of corresponding position sensor and so on.

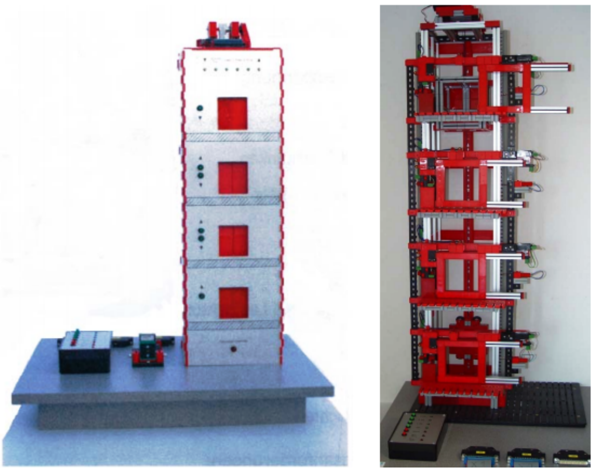

Figure 3. Physical models "elevator of the 4th floors" at GOLDi laboratory

TABLE II.
STRUCTURE OF THE MODEL CO_1

Assembly	Element	Type of actuator control	Sensor output
Mechanism of the cabin elevator	Electric motor	Up/down	
Cabin	Door mechanism	To open/close	
	Door sensors		On/off
	Lamps in cabin	To switch on/off	
	Buttons in cabin		On/off
Floor	Position sensor		On/off
	Lamps on the floor	To switch on/off	
	Call buttons		On/off

TABLE III.
STRUCTURE OF THE MODEL CO_3

Assembly	Graphical object	Tag/control type
Building	Building	-
	Cabin	Cabin position/vertical displacement
Cabin	Door	Door position/horizontal displacement
	Lamp	Lamp state/color
	Button	Button state/ assignment of the value to tag
Floor	Lamp	Lamp state/color
	Button	Button state/ assignment of the value to tag

Elements of visual model of the hidden part of the virtual elevator (CD_4 model) include, for example, graphical objects which displays the temperature of the electric motor of the cabin drive, the position of the elements of the emergency control and state of the cable tension sensor.

Elements of visual model of the external factors dynamics (model CO_5) are graphical objects of type "trend", reflecting the change of the external factors variables in the coordinates of model time. That may be the ambient temperature, the flow of elevator calls from the floors.

Elements of the visual model of the technical state (model CO_6) reflect the current number of no-fault cable strands, the remaining service life of the elevator equipment, elevator FSM graph.

Elements of the virtual model of the elevator (CO_7) convert values of variables of other RL models in graphical objects control parameters of model CO_3. For example, the value of "moving up" and displacement time are transformed into the tag value "vertical position of the cabin".

Examined structure of the models are created by the RL server for each pair of "laboratory model (physical or virtual) – remote student".

One more example of the RL integrated system is scenario 6 implementation for model Traffic Light, included in Remote Laboratory for Embedded Systems Design (RELDES) [10, 17]. Scenario steps are presented in Table IV.

At the 1st step it is proposed to choose type of diagram CO_1, which differs in polarity, mutual position LED and resistors, power source pole. Let CO_1 diagram shown in Fig. 4 is chosen.

TABLE IV.
SCENARIO 6 STEPS FOR MODEL "TRAFFIC LIGHT"

Step	Solution variant
0. Statement of the main task of traffic light model (on LED indicators) control	Infinite loop with red, yellow, green, yellow phases, duration of which are given by constants
1. Choice of main task solution principles	Logic level generation on control board digital output for each LED with taking into account LED connection and its light time duration. So, if LED is connected according to common-cathode circuit – HIGH level for the light (ON state) and the level of LOW – for quenching (OFF state)
2. Formalization LED state control sequences for solution of the main design task	Design of system FSM graph
3. Analysis of possible system faults, system behavior at emergences and actions required for fault detection	Critical defect – any break in circuit "board output – LED – resistor – power supply". System behavior – wrong indication. Actions – voltage control of ON state LED, failure indication
4. Correction of electric circuit and system behavior, taking into account the problem of possible failures detection	Choice of a diagram provided voltage measurement across the circuit section with LED and additional LED ERROR. Introduction of additional states in the FSM graph, for example, state ERROR
5. Simulation of LED defects during system operation time	Replacing in a certain time moment HIGH level to LOW level at the output of the control board, which controls the LED or turn-off of the transistor, which is in-series with LED. Development of FSM graph for defects simulation
6. Development of set-theoretic models of local subsystems for design task	Development CO_1, CU_1 with FSM, DS_1, CO_4, CU_4, DS_4, CO_6, CU_6, DS_6
7. Implementation of design task set-theoretic models of local subsystems in RL on the basis of units with computing power	Implementation of local subsystems in the control program of the microprocessor

At the 2nd scenario step for the main control task graph FSM CU_1 is designed (see Fig 5).

After choice of the critical defect (step 3) correction of the diagram CU_1 is carried out (instead of diagram in Fig 4. diagram shown in Fig.6 with voltage measuring circuits and failure indication is chosen and designed).

System DS_1 is presented in Fig.7, where DO is digital output pin; AI is analog input pin of the microprocessor board. Changes in DS_1 structure are designed (imaged) in FSM graph (Fig.8) by addition of additional states Error-RYG, ErrorE and event transfers ErrorR, ErrorY, ErrorG, ErrorE. These events are the evaluation result of the LED voltage measuring, for example:

$$ErrorR=(TestR<U_{LEDmin})\&(DO_1=ON),$$

where U_{LEDmin} is digital code of the minimal voltage on faultless LED in ON state.

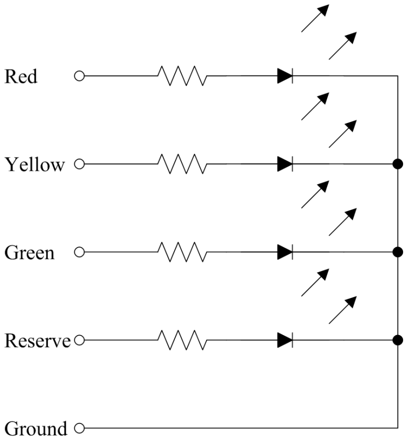

Figure 4. Model CO_1 "Traffic Light"

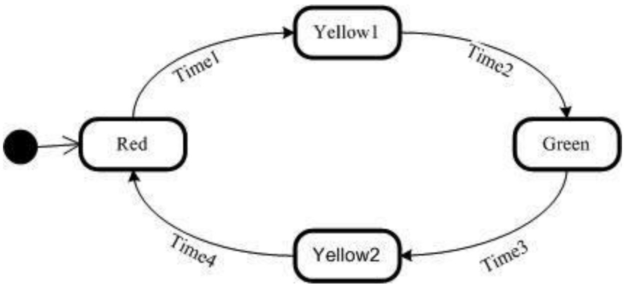

Figure 5. FSM graph CU_1 for the main task of the traffic light

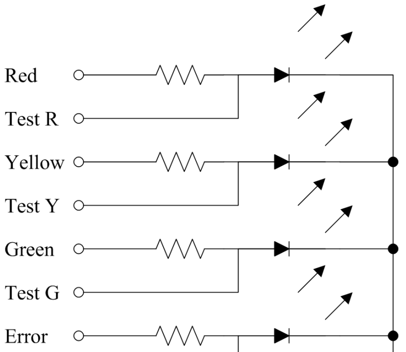

Figure 6. Model CO_1 "Traffic Light" with LED voltage measuring circuits

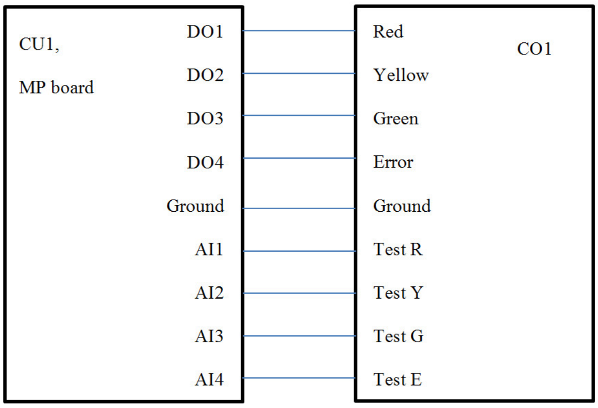

Figure 7. Model DS_1 “Traffic Light”

The state ErrorE is introduced to represent the situation when both are faulty, at least one of Red, Green, Yellow LED and the LED “Error".

FSM CU_1 can be defined in a similar form:

$$<X, Y, S, S_0, \mu, \sigma>,$$

where X, Y, S is set of inputs (event), outputs and states of FSM CU_1 correspondingly; S_0 is initial state; μ is matrix of outputs σ – matrix of transfers;

X={Time1, Time2, Time3,Time4, ErrorR, ErrorY, ErrorG, ErrorE};

$$Y=\{DO_1, DO_2, DO_3, DO_4\};$$

S={Red, Yellow1, Green, Yellow2, ErrorRYG, ErrorE};

S_0=Red;

μ:	State	DO_1	DO_2	DO_3	DO_4
	Red	ON	OFF	OFF	OFF
	Yellow1	OFF	ON	OFF	OFF
	Green	OFF	OFF	ON	OFF
	Yellow2	OFF	ON	OFF	OFF
	ErrorRYG	OFF	OFF	OFF	ON
	ErrorE	Blink	Blink	Blink	Blink

σ:	Old State	Event	New State
	Red	Time1&!ErrorR	Yellow1
	Yellow1	Time2&!ErrorY	Green
	Green	Time3&!ErrorG	Yellow2
	Yellow2	Time4&!ErrorY	Red
	Red	ErrorR	ErrorRYG
	Yellow1	ErrorY	ErrorRYG
	Green	ErrorG	ErrorRYG
	Yellow2	ErrorY	ErrorRYG
	ErrorRYG	ErrorE	ErrorE

Where “!” is inversion sign; Blink is blinking mode of outputs – indication method of the LED (Red or Yellow or Green) failure at simultaneous LED Error failure.

RL RELDES peculiarity is absence of simulation screens of the system operation. Correctness of the designed system is checked visually by the image, obtained from WEB-camera (subsystem DS_2). That’s why model DS_3 is not considered. Another RELDES peculiarity is that there are no computational nodes for implementation of DS_4 model in RL system. Therefore DS_4 (hidden part of CO_1) functions should be taken into consideration in physical model diagram, for example as it is shown in Fig. 6.

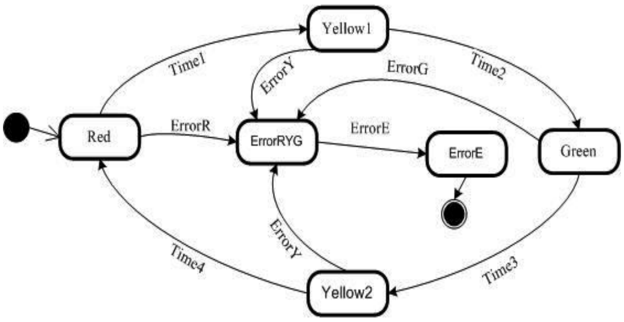

Figure 8. FSM graph CU_1 for the traffic light with LED test

DS_6 (failure generation) functions is implemented in control program, executed on the microprocessor board.

For this purpose on formed by FSM value of inputs states are imposed. For example for input:

$$DO_1=DO_1\&!genErr,$$

where genErr is failure simulation attribute.

If genErr=ON is assumed that LED transferred into failure state and DO_1 possesses the value OFF irrespective of the value, formed by FSM. For genErr generation e.g. number of infinite control program operation loop can be used. Fragments of the sketch control the traffic light with function of LED failure detection is presented in Fig. 9.

II. CONCLUSIONS

1. RL functional structure and studied objects models used in it are important descriptive elements of the RL properties and features. The structure of the models, their variants, properties, studied objects functionality inheritance should be determined at the IEEE level in RL.

2. Analysis of the functional elements of a remote lab in coordinates “control object – control unit” showed that some elements function as the control object in one local system, and the control device in the other. Set-theoretic models of studied objects physical, virtual and visual models describe RL as an integrated control system.

3. It was proposed to extend the studied objects hybrid model in RL. To known structure it was added a subsystem of a “hidden” part, studied objects technical state and environment, which interact with studied objects physical and virtual models. These additions increase the functionality of studied objects model, which allows setting more complex design tasks for students and increasing a number of experiments with physical models without their modification.

4. Taking into account the additional possibilities of hybrid models it was offered additional scripts of RL usage. To the basic scenario “programming of logic control algorithms of serviceable studied objects” it was added: “definition of the studied objects structure and state by monitoring of its operation”, “experiments with actuators of studied objects physical virtual model”, “check of studied objects control algorithms using tests”, “development of studied objects verificatory and diagnostic tests”, “development of control algorithms for studied objects emergency operation” and “operator’s simulator”.

```
void loop() {
//Actions in the state
if ( stateR&&(!genErrRed)) { digitalWrite(redPin, HIGH); } else
digitalWrite(redPin, LOW);
…..
if  (stateErrRYG&&(!genErrError))  {  digitalWrite(errorPin,
HIGH);} else digitalWrite(errorPin, LOW);
if  (stateE)  {  for  (thisPin  =  1;  thisPin  <=  4;  thisPin++)
digitalWrite(thisPin, HIGH);delay(100);
for (thisPin = 1; thisPin <= 4; thisPin++) digitalWrite(thisPin,
LOW); delay(100);};
//The event generation
analogValue = analogRead(analogRedPin);  if ((analogValue <
normVoltageLed)&&stateR) {eventErrRYG = HIGH;};
….
if (!stateE) {delay(10);  timeState = timeState + 10;};
if ((stateR)&&(timeState>=time1)) eventEndR = HIGH;
…. //Generating errors
loopNumber++;      genErrRed  =  LOW;    if  (loopNumber  >=
loopBeforeRed) genErrRed = HIGH;
….  //Changing states
if ((stateR)&&(!genErrRed)&&(eventEndR))  { stateY1 = HIGH;
stateR = LOW; eventEndR = LOW; timeState = 0;};
….
if  ((stateR)&&(genErrRed))   {  stateErrRYG  =  HIGH;  stateR  =
LOW; eventEndR = LOW; timeState = 0;};
….
if  ((stateE)&&(genErrRed)&&eventErr)    {  stateE  =  HIGH;
stateErrRYG = LOW;  timeState = 0;};
}
```

Figure 9. Fragments of the sketch control the traffic lights with function of LED failure detection

5. The usefulness of the hybrid model of the studied object shown in the example scenario of teaching design of the traffic light. In this scenario, the functionality of a traditional physical model of the traffic lights (indication LED Red/Yellow/Green) complemented by diagnostics of the technical condition of LED. Hidden CO and State Technical subsystems included in a hybrid model of traffic lights for the implementation of this function.

These scenarios are supposed to be used for the design of remote laboratories in Zaporizhzhya National Technical University as a part of international program "Tempus" ICo-op for creation of the training courses for distance engineering education in the directions "Electromechanics" and "Software Engineering" based on remote engineering and virtual instruments [3, 18].

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AUTHORS

Mykhailo Poliakov, is with Zaporizhzhya National Technical University, Electrical and Electronic Apparatuses Department, Zhukovskogo, 64, Zaporizhzhya, 69063 Ukraine. (e-mail: polyakov@zntu.edu.ua).

Tetiana Larionova, is with Zaporizhzhya National Technical University, Electrical and Electronic Apparatuses Department, Zhukovskogo, 64, Zaporizhzhya, 69063 Ukraine. (e-mail: newweb.author@gmail.com).

Galyna Tabunshchyk is with the Zaporizhzhya National Technical University, Software Tools Department, Zhukovskogo 64, Zaporizhzhya, 69063 Ukraine, (e-mail: galina.tabunshchik@gmail.com).

Anzhelika Parkhomenko is with the Zaporizhzhya National Technical University, Software Tools Department, Zhukovskogo 64, Zaporizhzhya, 69063 Ukraine, (e-mail: parhom@zntu.edu.ua).

Karsten Henke is with Ilmenau University of Technology, Ilmenau, Germany. (e-mail: karsten.henke@tu-ilmenau.de).

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