

# Modeling and Computer Simulation of Static, Dynamic and Feedback Systems as Tool of Development of Logical Thinking

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**Abstract**—Many universities are realizing that modeling and simulation is becoming an important tool in finding the strategy for solving and understanding numerous and diverse problems. The paper introduces the theory of modeling and simulation as one of the possible method in the education. The theory is followed by three case studies illustrating step by step process of development of modeling and computer simulation. The first two cases studies will present possibility of simulation of static and dynamic systems in MS Excel worksheet and chart. The third case study presents creation of simulation model of the feedback regulated process – passing through the labyrinth.

**Keywords**—Dynamic System, Feedback System, Modeling and Simulation, Static System.

## I. INTRODUCTION

THE term “developing of theoretically acquired knowledge” can be connected with the terms “system”, “model”, “computer simulation”, “dynamic visualization”, “animation” or “multidisciplinary approach”, which are important in current approach to not only scientific, technological and professional practice but also in high school education of science subject.

The first two cases studies will present possibility of simulation of static and dynamic systems in MS Excel worksheet and chart. Presented case studies are used in the learning of programming in study program Physical Measurement and Computer Science Departments of Physics and Department of Informatics, Faculty of Science University of Hradec Králové.

The third case study presents creation of simulation model of the feedback regulated process – passing through the labyrinth realized and verified by real device constructed from LEGO® MINDSTORMS® robotic system.

## II. PROBLEM FORMULATION

System approach is closely related to the concept of system. The system in general terms can be based on e.g. understood as a defined set of elements and relationships that creates an integrated whole. The system is also part of external reality

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and communicates with its environment through its inputs and outputs. System with no links to the surroundings is closed system.

In connection with the concepts of system and system approach is necessary to mention the other term that is commonly used – interdisciplinarity. This concept can be understood as a method of linking and active cooperation between different sciences in order to achieve integrated and synergistic results in theoretical and practical professional activities, science and research.

The systems approach rather than interdisciplinarity talk about multidisciplinary. A multidisciplinary approach is used mainly in the method of solving problems and creating technically functional units, such as the creation of the computer program – see e.g. [1]. The main reason for the introduction of multidisciplinary in connection with the system and a systems approach is that the research system as a whole requires a high degree of highly specialized knowledge in different disciplines and these specializations has to be closely linked by mutual connection. Only a multidisciplinary approach will ensure that the whole system will be studied systematically and comprehensively.

Although the interdisciplinary approach in the context of learning process is frequently discussed, the concept of system approach in educational practice is not sufficiently specific and widely implemented.

### A. System approach and education

System approach, scientific modeling and computer simulation are the terms which are closely related.

System approach enables description of the real processes, without which mathematical model and computer simulation model cannot be realized.

From the education point of view the system approach can be applied:

- In the field of sciences - in case of models and simulations of science processes and phenomena;
- In the technical field - in case of the process control of machines and simple robots;
- In the humanities and social studies - in case of the processes and phenomena associated with this issue;
- In management - in case of the management processes and quality control processes.

The other information on system approach in education can be found e.g. in [2], [3].

### B. Modeling

The main goal of modeling is not only describing the content, structure and behavior of the real system representing a part of the reality but also describing the processes. The process can be understood as series of transformations that changes the input values to output values. From the system point of view the process is dynamic system in which the values of the characteristic of the system elements are changed under the influence of the external elements. The first step in the process of computer simulation is creation of conceptual model of the studied real system / real process. Conceptual model can be represented in different way. The most used representations are:

*Mathematical equitations* establishes mathematical model of the studied real system. The model can be obtained either theoretically based on basic physical properties of the system, or numerically by means of the measured values. Determination of parameters of theoretical model developed from empirical data is called system identification.

*Scatter chart (scatter plot)* is a type of mathematical diagram using Cartesian coordinates to display values for two variables for a set of data in 2D types of the chart. The scatter plot takes two sets scalar variables and uses them for two axes in 2D space. Time depending variables create dynamic scatter chart representing time depending conceptual model of the dependency of system outputs on its inputs.

*Flowchart* is a type of diagram that represents algorithm or modeled process. The flowcharts are represented in the form of boxes of various kinds (inputs/outputs, processing, conditions, cycles) ordered by connecting them with arrows. Flowcharts are used in analyzing, designing, documenting or managing a process in various fields.

Modeling of the static system of real phenomena will be shown in the first case study of this paper.

Modeling of the dynamic system of real phenomenon will be shown in the second case study of this paper.

Modeling of the real process will be shown in the third case study of this paper.

### C. Simulation

The process of modeling is closely related to the simulation. Simulation can be understood as process of executing the model. Simulation enables representation of the modeled real system or real process and its behavior in real time by means of computer. The simulation enables also visualization and editing of the model.

A typical simulation model can be written both through specialized programming languages that were designed specifically for the requirements of simulations, or the simulation model can be created in standard programming

languages.

From the above considerations, it is clear that simulation is a process that runs on the computer. In some publications, therefore, can be found the term "computer simulation". It generally is valid that computer simulation is a computer-implemented method used for exploring, testing and analysis of properties of the conceptual (mathematical or process) models that describe the behavior of the real systems or real process which cannot be solved using standard analytical tools, which is discussed e.g. in [4], [5].

Simulation of the static system of real phenomena via 2D scatter chart created in MS Excel program will be shown in the first case study of this paper.

Simulation of the dynamic system of real phenomenon via 2D scatter chart created in MS Excel program will be shown in the second case studies of this paper.

Simulation of the real process (passing through the labyrinth) will be shown in the third case study of this paper.

### D. Simulation of feedback regulated systems and process

Many real systems as well as real processes are constructed so that they are able control themselves by means of the feedback [6].

Feedback is a mechanism that is looped back to control a system / process within itself. Such a loop is called a feedback loop. In the system or process containing the feedback loop the input characteristics or signals are influenced by output characteristics or signals.

The computer simulation is essential method not only for representation of the conceptual model but can also be used for investigation of the feedback affected processes.

Feedback affected behavior of the real process will be shown in the third case study of the paper.

### E. Significant function of the simulation

Simulation has from the scientific point of view several functions – see e.g. [7].

We will focus in this paper two of them and they are:

- replacing the real process;
- development of educational process.

#### 1) Replacement of the real process

This is an important and indispensable feature of simulations and simulation model because it allows realize a situation of the process that cannot be investigated conventionally. The main advantage of simulations is that simulations model allows providing rather big number of the process steps in relatively short time, changing of input parameters and its visualization and optimization of the process.

#### 2) Development educational process

The simulation is very useful from educational point of view. Using the simulation model and visualization of simulation results on the screen, students can better understand the basic features of the processes and systems and

develop their intuition. It is also essential that the teaching by means of simulation is much cheaper and faster than the teaching carried by real experiment. In some cases providing the real experiment cannot be feasible.

#### F. Model verification and validation

Verification and validation are important aspects of the process modeling and simulation. They are essential prerequisites to the credible and reliable use of a model and its results [9].

##### 1) Verification

In modeling and simulation, verification is typically defined as the process of determining if executable simulation model is consistent with its specification – e.g. conceptual model. Verification is also concerned with whether the model as designed will satisfy the requirements of the intended application. Verification is concerned with transformational accuracy, i.e., it takes into account simplifying assumptions executable simulation model. Typical questions to be answered during verification are:

- Does the program code of the executable simulation model correctly implement the mathematical model?
- Does the simulation model satisfy the intended uses of the model?
- Does the executable model produce results when it is needed and in the required format?

##### 2) Validation

In modeling and simulation, validation is the process of determining the degree to which the model is an accurate representation of the real system / real process. Validation is concerned with representational accuracy, i.e., that of representing the real system / real process in the conceptual model and the results produced by the executable simulation model. The process of validation assesses the accuracy of the models. The accuracy needed should be considered with respect to its intended uses, and differing degrees of required accuracy may be reflected in the methods used for validation. Typical questions to be answered during validation are:

- Is the mathematical model a correct representation of the real system?
- How close are the results produced by the simulation executable model to the behavior of the real system?
- Under what range of inputs are the model's results credible and useful?

Validation and verification are both ultimately activities that compare one thing to another. Validation compares real system / real process and conceptual model. Verification compares conceptual model and executable simulation model. Sometimes validation and verification are done simultaneously in one process.

Validation of the conceptual model as well as verification of the simulation model of our real process – *passing through the labyrinth* – are to be done simultaneously by running simulation computer model.

#### G. Process of modeling and simulation

The whole process of transformation from a real system, the simulation model and its visualization is shown in Figure 1.

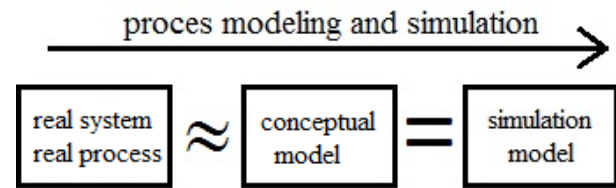


Fig. 1 Process modeling and simulation

Here again let us summarize that the mathematical model that reflects the real system / real process has some limitations and simplifying assumptions (the real system / process and conceptual model are in homomorphic relation).

In contrast, the simulation model is only the computer expression of the conceptual model (the conceptual model and simulation model are in isomorphic relationship).

#### H. Multidisciplinary approach

Another important benefit associated with the modeling and simulation of real processes is a multidisciplinary approach, without which the identification of the real processes using conceptual and simulation model and cannot be realized. This is also emphasized in this paper.

Multidisciplinary approach generally means that specialized disciplines are applied in a study of real process. These disciplines provide partial analysis of the process. These mono-disciplinary analyses are integrated to overall solution by integrating the solver who has basic multi-disciplines knowledge.

In our case study four disciplines are integrated, namely, algorithm development, programming and mathematics.

### III. CASE STUDY 1 - SIMULATION OF STATIC SYSTEM

Case study of the simulation of static system in MS Excel chart will be demonstrated by creation of rainbow function. Before starting the discussion on simulation model we analyze the problem from mathematical and physical point of view.

#### A. Mathematical model

The system is based on principles of reflection and refraction of light. In reflection and refraction the reflected (refracted) ray remains in the plane of impact. The plane of impact is determined by two straight lines – an impact ray and a perpendicular to the optical boundary in the place of impact. Moreover for the reflection is valid that angle of reflection is equal to the angle of impact – i.e.

$$\alpha = \alpha' \quad (1)$$

For refraction is valid that the proportion of the sine of angle of impact to the sine of angle of refraction is equal to the relative index of refraction – i.e.

$$\frac{\sin \alpha}{\sin \beta} = n. \tag{2}$$

Other well know condition that the sum of the inner angles

of triangle is always 180°, in tetragon it is 360°, in pentagon it is 540°, and that the correspondent top angles are equal.

With the use of the Figure 2 it is relatively easy to derive right formula for rainbow function.

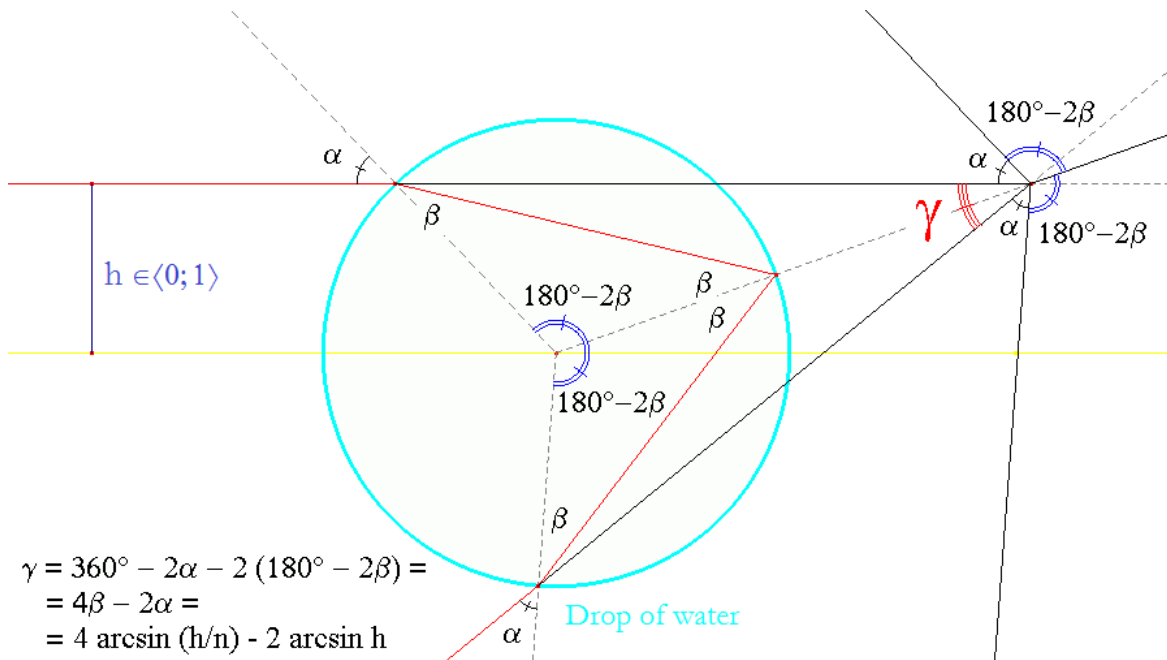


Fig. 2 Derivation of formula for rainbow function

Because sum of angles in right top corner in figure 1 is the full angle, so we can write:

$$\gamma = 4\beta - 2\alpha. \tag{3}$$

Angle  $\alpha$  is the angle of incidence, so  $\sin \alpha = h$ , therefore  $\alpha = \arcsin h$ . Similarly angle  $\beta$  is the angle of refraction, so  $\sin \alpha = n \sin \beta$ , therefore  $h = n \sin \beta$  and  $\sin \beta = \frac{h}{n}$ , therefore

$$\beta = \arcsin \frac{h}{n}.$$

That for the resulting angle of refraction  $\gamma$  on a drop of water is valid this relation:

$$\gamma = 4 \arcsin\left(\frac{h}{n}\right) - 2 \arcsin(h). \tag{4}$$

where  $h$  is a relative distance of the dropping ray from the parallel ray crossing the center of the drop (the real number from 0 to 1). The  $n$  is the relative index of refraction for the transition of the ray from air to water. Because the absolute index of air refraction is normally very close to 1 (1.00026), it is possible to substitute the absolute index of the water refraction for  $n$ .

A. Simulation model

Rainbow function  $\gamma$  is real function of one real variable  $h$  (see equitation (4)), where index of refraction  $n$  that depends

on a wave length (and also on the colour) of the dropping light is a parameter. The process of function for three different amounts of refraction index  $n_R = 1.330$  (red light),  $n_G = 1.334$  (green light), and  $n_B = 1.337$  (blue light) can be calculated and depicted as a function type X-Y in the spreadsheet.

Construction of the simulation model in MS Excel is as follows.

In the spreadsheet MS Excel we prepare amounts of the independent variable  $h$  from 0 to 1 with the step of 0.01 in the column A and for this column we define a title  $h$  in the bookmark "Formula" by the function "Define title...".

Columns B, C and D we name RED, GREEN and BLUE. In the second line of the chart we state the amounts of indexes of refraction and choose for them a title  $n$ .

Then we can write the formula:

$$=(4*ARCSIN(h/n)-2*(ARCSIN(h))*180/PI())$$

to the top left cell (B4). The formula figures out the amount of the function  $\gamma$  in radians and by multiplying it with  $180/\pi$  it transfers it to the angle degrees. Then we copy the formula to the right and down to the whole area of the outputting amounts.

We use graph X-Y with the smoothed connectors and with the grid for more precise deduction of amounts. We re-colour the colours of individual lines so that they correspond to the three chosen colours of the Sun light spectrum.

Simulation model is shown on the Figure 3. Detailed

information can be found in [8].

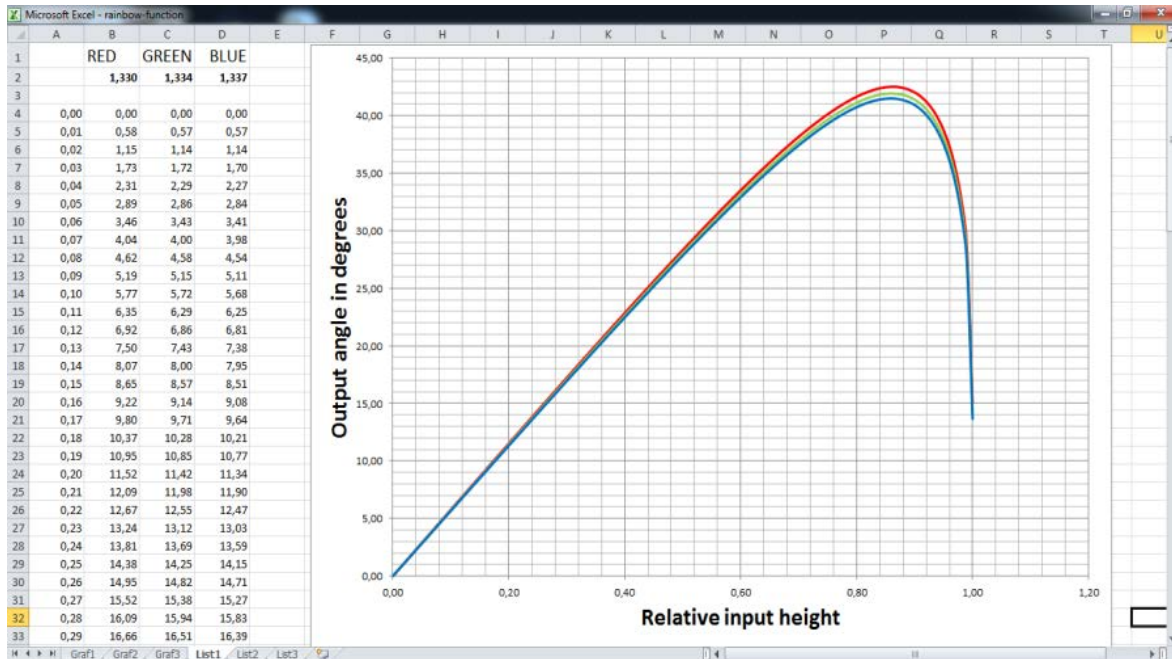


Fig. 3 Static simulation model of rainbow function

#### I. CASE STUDY 2 - SIMULATION OF DYNAMIC SYSTEM

Case study of the simulation of dynamic system in MS Excel chart will be demonstrated by creation of animation of ballistic trajectory. Before starting the discussion on simulation model we analyze the problem from mathematical and physical point of view.

##### A. Mathematical model

Ballistic trajectory is trajectory of the flight projectile moving in the air. The main forces acting on the projectile are gravity, and air resistance. Gravity imparts a downward acceleration on the projectile, causing it to drop from the line of sight. Air resistance, decelerates the projectile with a force proportional to the square of the velocity. During flight, gravity and air resistance have a major impact on the path of the projectile, and must be accounted for when predicting how the projectile will travel.

The ballistic trajectory is given by equations of motion. The equations of motion in the  $x$ , resp.  $y$  directions are:

$$ma_x = -kv_x, \quad (5)$$

$$ma_y = -mg - kv_y, \quad (6)$$

where  $m$  is mass of the projectile,  $k$  is coefficient of the air resistance,  $a_x$  resp.  $a_y$  are accelerations,  $v_x$  resp.  $v_y$  are velocities and  $g$  is gravity acceleration.

The equations (5) and (6) can be solved either analytically or numerically. We will show in the paper numeric solution.

Numeric solution is based on splitting the trajectory of the

ballistic motion to number of the small time elements  $dt$ . The solution is as follows:

$$t_{n+1} = t_n + dt, \quad (7)$$

$$(a_x)_n = -k(v_x^2)_n, \quad (8)$$

$$(a_y)_n = -k(v_y^2)_n - g, \quad (9)$$

$$(v_x)_{n+1} = (v_x)_n + (a_x)_n dt, \quad (10)$$

$$(v_y)_{n+1} = (v_y)_n + (a_y)_n dt, \quad (11)$$

$$(x)_{n+1} = (x)_n + (v_x)_n dt, \quad (12)$$

$$(y)_{n+1} = (y)_n + (v_y)_n dt, \quad (13)$$

with initial conditions:

$$(v_x)_0 = v_0 \cos \alpha, \quad (14)$$

$$(v_y)_0 = v_0 \sin \alpha, \quad (15)$$

$$(x)_0 = 0, \quad (16)$$

$$(y)_0 = h, \quad (17)$$

where  $v_0$  is initial velocity of the projectile shoot,  $\alpha$  is angle of the shoot and  $h$  is initial height of the shoot.

### B. Simulation model

Simulation model of ballistic curve is based on animation of ballistic trajectory.

Animation in general means a way how a static image can be seemingly set in motion. The principle of an animation is recording of a sequence of images which slightly differ.

The principle of the animation of the scatter chart in MS Excel is based on the change of one or more parameters of the charts input data of the dynamic objects or curves. The objects or curves step by step change its position in relation to the static baselines which are time dependence function of one or more parameters. A change of these parameters can be achieved by using so-called *iterative calculation* of values in the cell – for more detail see [3], [4], [5].

Main parameter responsible for iterative recalculation is time  $t$ . The trajectory will be drawn step by step from time  $t = 0$  with the time increment  $dt$ .

The value of the actual time  $t$  is saved in e.g. cell D2. The value of time increment  $dt$  is saved e.g. in cell D10. The circular reference formula  $= D2 + D10$  is entered into cell D2. This formula expresses that the value of time in D2 after one iterative recalculation step increases by the increment time  $dt$  - iteration (animation) step.

By repeated pressings, eventually by holding down the key **F9**, the value of cell D2 will step by step increase by the value of the animation step – value in cell D10.

If only the formula  $= D2 + D10$  was entered to the cell D2, the value of D2 would after each iteration step still increase. It is therefore necessary to determine the *terminating condition*, i.e. *minimum* and *maximum* time limits.

Minimum time is  $t = 0$  s. Maximum animation time  $t_{max}$  is given by time, when  $y$  coordinate of the projectile is less than

0.

This can be done by adding the following condition to formula in cell D2:

$$= IF (MIN(\$S:\$S)<0;0;D2+D10)$$

Principle of the iterative recalculation of the cell D2 and setting of initial conditions is shown on Figure 4.

D2		fx		=IF (MIN(S34:S653)<0;0;D2+D10)	
A	B	C	D	E	F
1	<b>Animation of Ballistic Curve</b>				
2		$t$ [s]	1,70		
3					
4		<b>Initial conditions</b>			
6		$g$	9,81	$\text{ms}^{-2}$	
7		$v_0$	30	$\text{ms}^{-1}$	
8		$h$	5	m	
9		$\alpha$	50	$^\circ$	
10		$dt$	0,05	s	
11		$m$	1000	kg	
12		$k$	0,03		
13					

Fig. 4 Principle of iterative recalculation of D2

The solution of simulation model is shown on the Figure 5. Green line is ballistic trajectory, red line is trajectory of projective with no air resistance.

Detailed derivation of the mathematical model and detailed creation of the simulation model can be found in [5] and [9].

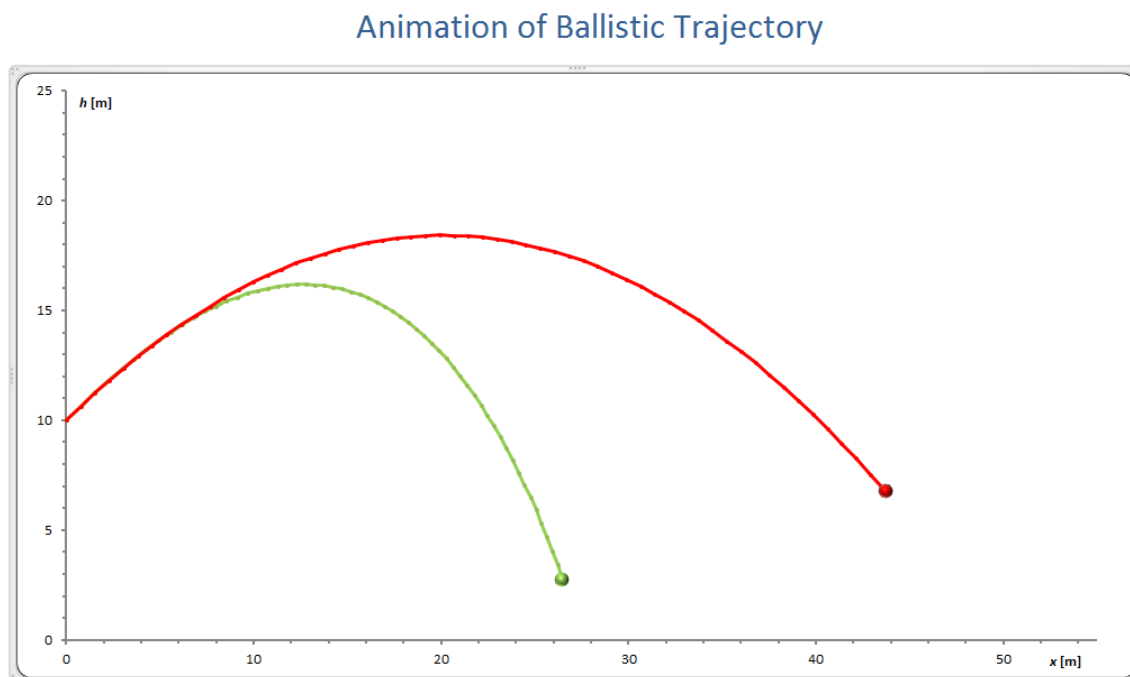


Fig. 5 Dynamic simulation model of ballistic trajectory



### I. CASE STUDY 3 - SIMULATION OF FEEDBACK PROCESS

This case study will demonstrate the solution of feedback process – passing through the labyrinth. The suggested algorithm of the solution has been verified by real device constructed from the LEGO® MINDSTORMS®.

#### A. Analysis of the problem

##### 1) Defining the labyrinth type

First, the labyrinth form has to be defined. Form of labyrinth is the main limiting factor to solution this specific problem and solution in the form of algorithm depend on it. There is also mutual relationship, between the labyrinth and sensors, which explains the need to use appropriate materials for incident-free detection by available sensors of labyrinth passing device. Detailed solution can be found in [ ] and [ ].

Some labyrinths are, for simplicity, only represented by a line, others only by walls, or the labyrinth can be defined by both above possibilities. Such approach is used, for example, for orientation in space on the boxes, which are usually defined by black line. Our solution will also use both approaches.

The black line will facilitate the orientation of the passing model in space that will form the axis of every possible way even the blind. The robotic model will keep the black line during its movement and no accidental deviation occurs from the desired direction during the rotation of model on angle of 90 degrees. The possible form of the labyrinth is shown on the Figure 6.

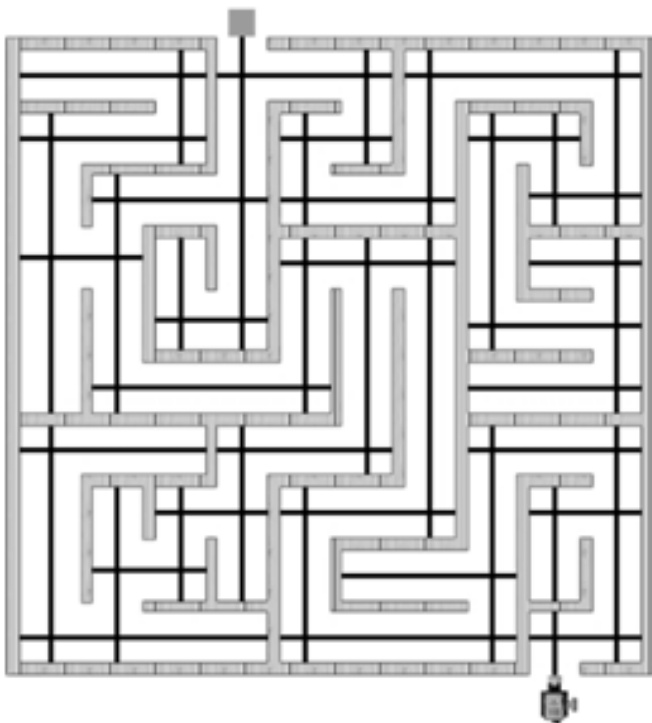


Fig. 6 Example of labyrinth

##### 2) Algorithm development passing through the labyrinth

The solution of passing through the labyrinth can be understood as feedback process, because the reaction of the passing device depends on the actual state of the device.

The actual state is detected by sensors. The sensors provide the identification of:

- black line: without / with intersections;
- walls: in front / on the right side of the device.

There are eight possible states and eight possible feedback reactions of the passing device – see e.g. [10] or [11].

##### *Straightaway* – Figure 7:

input:

- color sensors detect black color line, according to which varies the direction of travel;
- both ultrasonic sensors do not detect barrier;

feedback:

- the robot follows a line, so it goes straight.



Fig. 7 Straightaway direction

##### *Turn left* – Figure 8:

input:

- color sensors detect the crossing of the black lines;
- both ultrasonic sensors detect barriers;

feedback:

- the robot turn left 90 degrees;

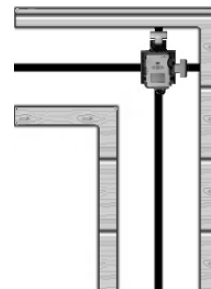


Fig. 8 Turn left

##### *Turn right* – Figure 9:

input:

- color sensors detect the crossing of the black lines;
- front ultrasonic sensor detects barrier;
- right ultrasonic sensor does not detect barrier;

feedback:

- the robot turn right 90 degrees;

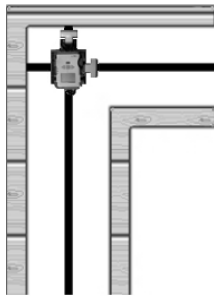


Fig. 9 Turn right

*Intersection left* – Figure 10:

input:

- color sensors detect the crossing of the black lines;
- front ultrasonic sensor does not detect barrier;
- right ultrasonic sensor detects barrier;

feedback:

- the robot goes straight;

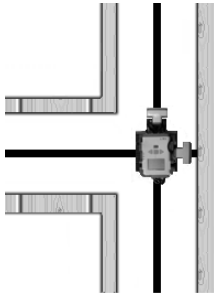


Fig. 10 Intersection left

*Intersection right* – Figure 11:

input:

- color sensors detect the crossing of the black lines;
- both ultrasonic sensors do not detect barrier;

feedback:

- the robot turn right 90 degrees;

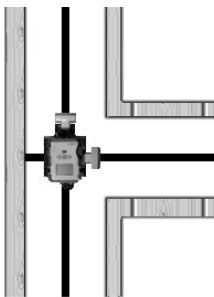


Fig. 11 Intersection right

*Intersection left / right* – Figure 12:

input:

- color sensors detect the crossing of the black lines;

- front ultrasonic sensor detects barrier;
  - right ultrasonic sensor does not detect barrier;
- feedback:
- the robot turn right 90 degrees;

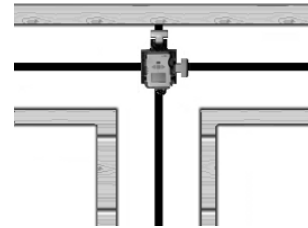


Fig. 12 Intersection left / right

*Intersection complete* – Figure 13:

input:

- color sensors detect the crossing of the black lines;
- both ultrasonic sensors do not detect barrier;

feedback:

- the robot turn right 90 degrees;

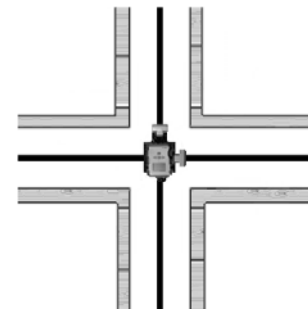


Fig. 13 Intersection complete

*Blind lane* – Figure 14:

input:

- color sensors detect black color line, according to which varies the direction of travel;
- both ultrasonic sensors detect barrier;

feedback:

- the robot turn back 180 degrees;

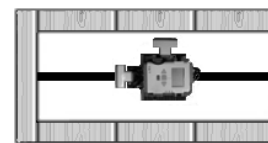


Fig. 14 Blind lane

The final algorithm of solution passing through the labyrinth is shown on the Figure 15 – for more detail see [11].



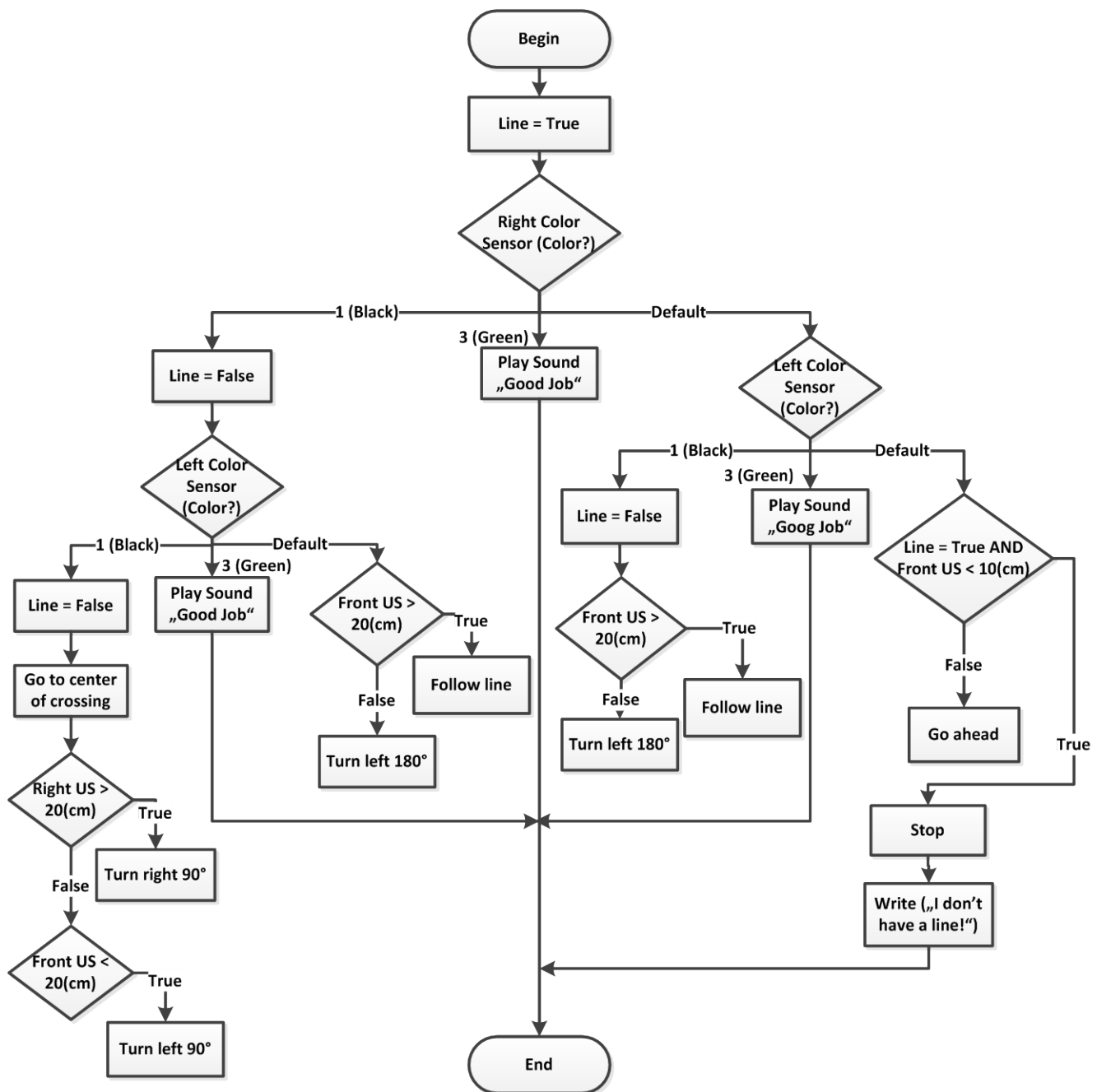


Fig. 15 Algorithm of the feedback process – passing through the labyrinth

## I. CONCLUSION

The paper offered one of the kinds of the possible teaching / learning strategies using the system approach including problem analysis. The system approach can be set as the default paradigm for a wide integration of the principles of the algorithm development into education. The authors highlight importance of utilizing systematic problem-solving approaches, like modeling and simulation or algorithm development for developing of logical thinking during educational process.

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