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The Concept and Application of Simplified Robotic Models

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Abstract: The use of robotic models with the main functionalities of real objects together with the implementation of innovative technologies, augmented reality (AR) in this case, is the focus of the paper. Therefore, the concept of a simplified robotic model (SRM) is presented. This concept is important because it is useful for achieving the goals of engineering projects, which is especially justified prior to the construction of the real objects. It improves presentation, development, and education capabilities that are unavoidable segments of the project strategy. Additionally, it is possible to transfer developed solutions to the final objects after certain modifications. Multidisciplinary building of the unique SRM of the 3-axis centrifuge for pilot training is described, where multi-attribute decision-making is used to conduct some experiments. The application includes the use of a physical model, built from LEGO elements, software for controlling and monitoring the physical model, and an AR mobile app.

Keywords: Simplified robotic models (SRM), Centrifuge for pilot training, LEGO, Augmented reality (AR), Multi-attribute decision-making (MADM).

1 Introduction

From the project management viewpoint, engineering projects can be very complex, time-consuming, and costly. Even understanding the risks can be a challenging task [1], so a very good strategy is required to be successfully completed. One way to facilitate such heavy tasks is to build and use models [2].

It is well-known that scientists use models, synthetic abstractions of real world [3] as a research method to replicate and analyse real-world systems [4]. Mathematical models are widespread in science and engineering [5]. While ideas can be considered as mental models, the use of physical models is not so

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widespread, except in architecture and related fields (where models are mostly static). On the other hand, it is shown that physical models supplement mental models in engineering idea generation [6]. In this paper, an advanced version of the physical robotic model (it is a robotic model because it must include two or more axes [7]), is introduced. Its broader role in the context of a strategic tool for achieving the goals of engineering projects that produce complex devices, are considered.

The very word “model” suggests that it is a simplified representation of the real object, i.e. it contains only the main functionalities of the actual object. As such, the concept of a simplified robotic model (SRM) presented in this paper includes the following main components:

- Physical model (refer to Subsection 4.1);
- Software for controlling and monitoring the physical model with remote control functionality (refer to Subsection 4.2);
- Additional options that are based on the use of innovative technologies and for which physical models are necessary, i.e. augmented reality (AR) mobile app in this case (refer to Subsection 4.3).

Specifically, the unique SRM of the centrifuge for pilot training is made according to the project requirements: *TR-35023 – Development of devices for pilot training and dynamic flight simulation of modern combat aircraft: 3-DoF centrifuge and 4-DoF spatial disorientation trainer*. It has three rotational axes (3-DoF centrifuge, Fig. 1): roll (x-axis) and pitch (y-axis), around which the pilot cabin rotates; and the vertical (planetary) axis around which the arm of centrifuge rotates (z_0-axis). The main dimensions are proportional to the real centrifuge in the approximate ratio of 1:20. Also, this SRM achieves the required number of revolutions per minute (RPM) and *G*-force.

Comparative views of the projected 3-DoF centrifuge [8] and built SRM of the centrifuge are shown in Fig. 1.

The authors explain, in the form of SWOT analysis, the reasons why they use LEGO elements for the construction of SRM of the centrifuge.

The main challenges and knowledge from the following fields needed for building SRM of the centrifuge are described in the paper:

- Mechanics – it is necessary to find appropriate solutions for torque transfer, i.e. appropriate gears construction, and to solve other construction tasks in order to satisfy all necessary requirements;
- Electrical engineering – this includes several tasks: designing a scheme of electrical devices connection, connecting all electrical components and without cable entanglement during rotations, using of sensors;

- Management – making decisions about the creation of any device is not an easy task because of the many criteria that need to be considered and analysed in a given context;
- Informatics – programming of device operation, data retrieving, making AR mobile app.

The main results include functional components of the SRM concept. Opportunities for the application of the concept are presented. Presentation, development, and education aspects in engineering projects are discussed. In this paper, the authors emphasize the importance of AR strategy, as an upgrade of the project strategy based on SRM, which is in line with the innovative development and use of innovative technologies.

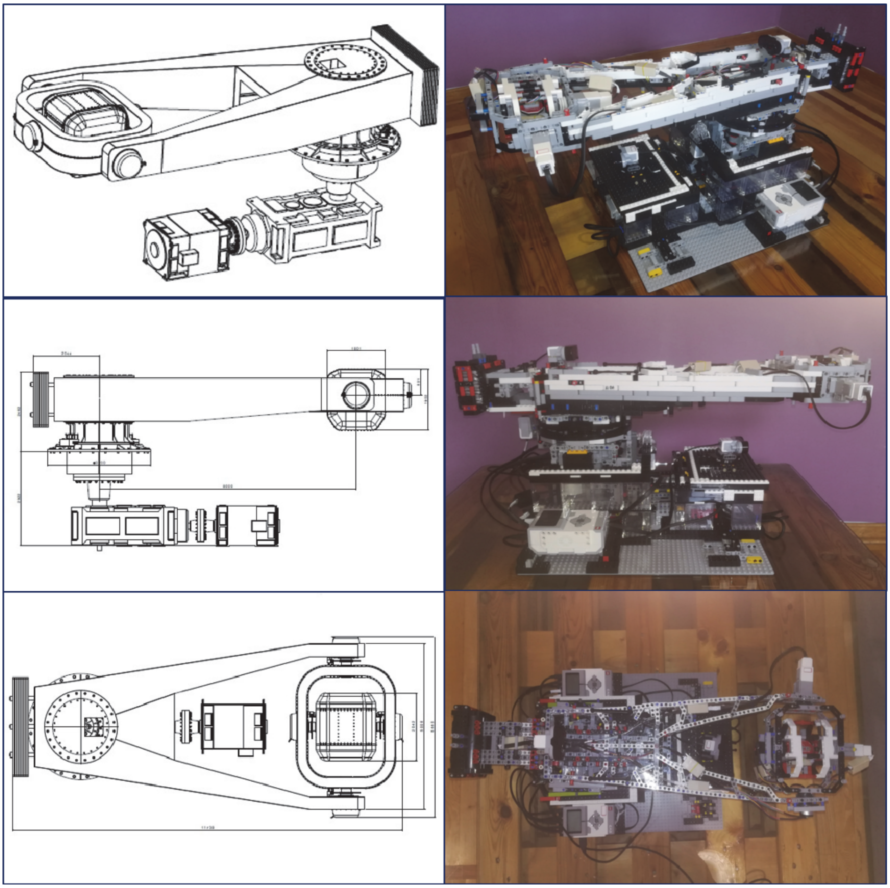
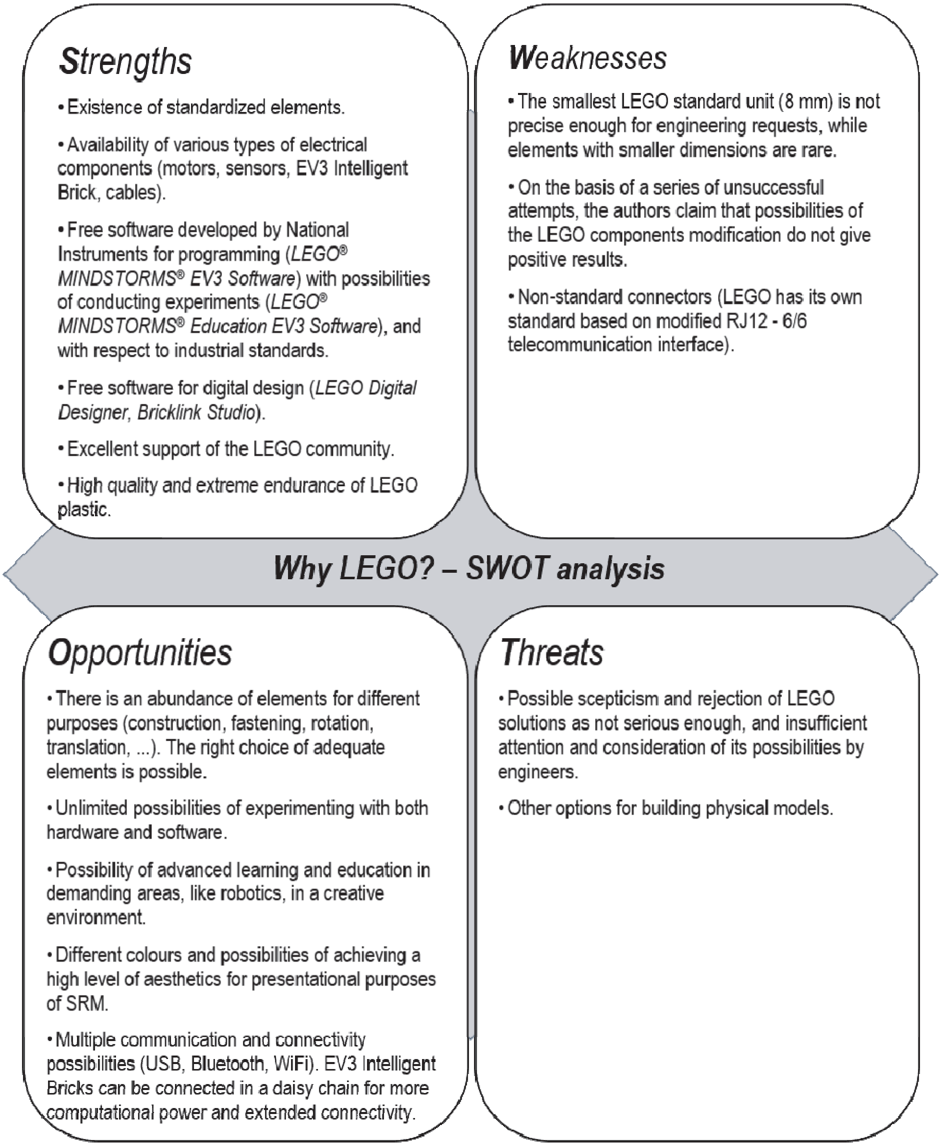


Fig. 1 – *Comparative views of the projected 3-DoF centrifuge and built SRM of the centrifuge.*

2 Why LEGO?

A primitive model of the centrifuge which did not have all functionalities (there were only two rotational axes) was built from LEGO elements at the end of 2018, as well as an AR/IoT mobile app under development [9]. In this paper, a new advanced version of this SRM is presented.



Why LEGO? – SWOT analysis

Strengths

- Existence of standardized elements.
- Availability of various types of electrical components (motors, sensors, EV3 Intelligent Brick, cables).
- Free software developed by National Instruments for programming (*LEGO® MINDSTORMS® EV3 Software*) with possibilities of conducting experiments (*LEGO® MINDSTORMS® Education EV3 Software*), and with respect to industrial standards.
- Free software for digital design (*LEGO Digital Designer, Bricklink Studio*).
- Excellent support of the LEGO community.
- High quality and extreme endurance of LEGO plastic.

Weaknesses

- The smallest LEGO standard unit (8 mm) is not precise enough for engineering requests, while elements with smaller dimensions are rare.
- On the basis of a series of unsuccessful attempts, the authors claim that possibilities of the LEGO components modification do not give positive results.
- Non-standard connectors (LEGO has its own standard based on modified RJ12 - 6/6 telecommunication interface).

Opportunities

- There is an abundance of elements for different purposes (construction, fastening, rotation, translation, ...). The right choice of adequate elements is possible.
- Unlimited possibilities of experimenting with both hardware and software.
- Possibility of advanced learning and education in demanding areas, like robotics, in a creative environment.
- Different colours and possibilities of achieving a high level of aesthetics for presentational purposes of SRM.
- Multiple communication and connectivity possibilities (USB, Bluetooth, WiFi). EV3 Intelligent Bricks can be connected in a daisy chain for more computational power and extended connectivity.

Threats

- Possible scepticism and rejection of LEGO solutions as not serious enough, and insufficient attention and consideration of its possibilities by engineers.
- Other options for building physical models.

Fig. 2 – *Why LEGO?*

The authors provide a SWOT analysis to explain why they decide to use LEGO elements and LEGO software for creating SRM of the centrifuge (for more information, please check Fig. 2):

- Strengths – the existence of standardized elements, availability of electrical components; free software for programming and digital designing; support of LEGO community; high quality of LEGO plastic;
- Weaknesses – it is not always possible to achieve desired precision; LEGO components are not suitable nor advisable for modification; non-standard electrical and data connectors;
- Opportunities – huge plentitude of elements; possibilities of experimenting with both hardware and software; possibility of advanced learning; possibility to achieve a high level of aesthetics; multiple communication and connectivity possibilities;
- Threats – possible scepticism by engineers; the existence of alternative options.

The SWOT analysis strongly suggests that LEGO is highly suitable for making SRM for even the most demanding projects. For some functionalities, it is possible to combine LEGO and third-party elements (in this case, third-party slip rings are used to conduct data without cable entanglement).

There are many examples of the application of LEGO models in the literature: for product prototyping [10], in robotic research – the CoRLEGO (*Choice reaching with a LEGO robot arm*) model [11], in robotic education [12, 13].

3 Multidisciplinary Building of SRM of the Centrifuge

In order to create complex SRM for the needs of engineering projects, a multidisciplinary approach and knowledge from multiple fields are needed. In this section, the authors describe the main challenges that appear during building SRM of the centrifuge.

3.1 Mechanics

One of the main challenges in building SRM of the centrifuge is torque transfer from motors to rotational part with an optimal ratio of power and rotational speed. In order to achieve this optimum, the authors tested several versions of gear trains. The outcome of the tests shows that characteristics of this object (a large mass of rotational part, long centrifuge arm) and forces that appear at high-speed rotational movement require specific gear train solution (Fig. 3). The top view shows only the topmost level of the drive train of the z_0-axis. There are three levels, each consisting of two large motors which drive two 36 T gears each. Each pair of 36 T gear drives one 12 T gear. All 12 T gears are located at the main shaft.

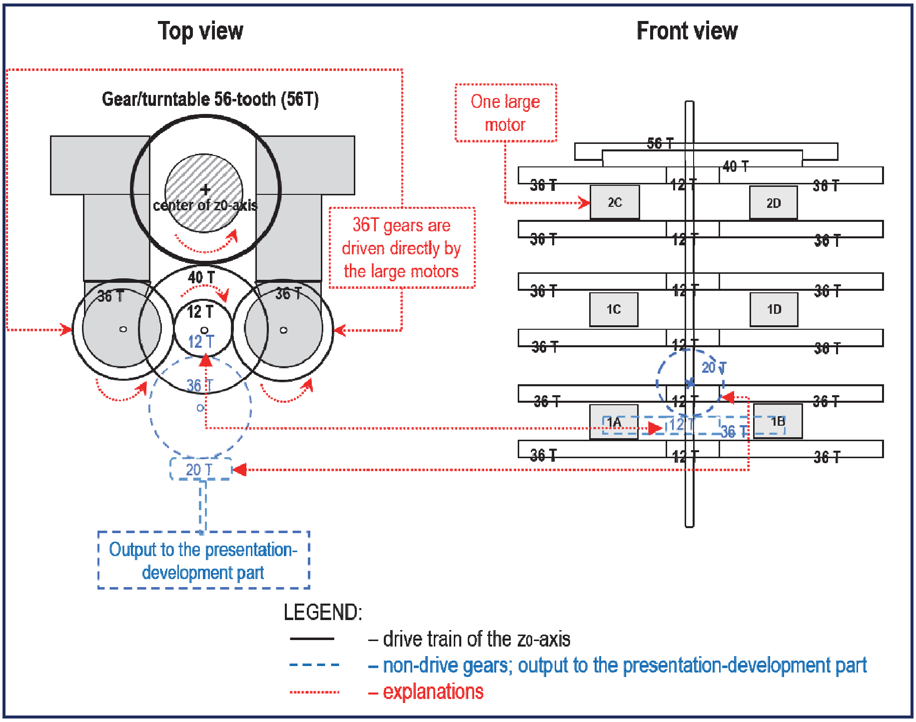


Fig. 3 – *Gears scheme: top view and front view.*

At the top of the main shaft, there is one 40 T gear that transfers torque to 56 T gear/turntable of the lower static part of it. The turntable has the static part which is toothed at the outer side and the rotary part which carries most of the mass of the centrifuge rotary part. In the middle of the turntable, there is a hole wide enough to pass through the wires (W) from the slip ring 24 W.

In total, the drive train of the z_0-axis consists of 6 large motors, 12×36 T gears, 6×12 T gears, 1×40 T gear, and 1×56 T gear/turntable (its axis lies on the z_0-axis of the centrifuge). The drive gear system provides a gear ratio of 2.14286, which enables speeding up the rotary part of the centrifuge.

Non-driving 12 T gear is mounted on the main shaft in the same way as driving 12 T gears. It is not connected to 36 T driving gears but to 36 T non-driving gear and outputs torque to the presentation-development part.

Large motors are organized in two groups, each consisting of three motors. One group must be inverted in order to rotate the main axis properly.

To alleviate the load that turntable carries on and in order to achieve a better distribution of the mass of the rotary part, one large rolling bearing is added, made of 8 LEGO Gear Racks 11×11 Curved, and some additional LEGO elements (specially designed rolling elements with a low friction coefficient).

Several other gear combinations are tested: 40 T gears on the motor shafts with 8 T gears mounted on the main shaft; 36 T on the motor shafts and 8 T on the main shaft; 40 T gears on the motor shafts with 16 T gears on the main shaft…). The best ratio of transferred torque and rotational speed at the full load of the rotational part of the centrifuge is achieved with the above-explained gear train. The LEGO community suggests the use of such gears for high loads and durability.

In the structural sense, this gear scheme had to be realized in very sturdy and stabile building in order to minimize vibrations and other unwanted effects. Such structure is achieved by using LEGO beam frames as the main structural part in the drive train. In this way, all the gears are connected tightly and steadily.

Additionally, the choice of the optimal mass of counterweight is extremely important. Similarly, as on a real object, it heavily influences the stability of the whole device.

The magnitude of acceleration acting on the pilot head, $a=(a_n^2+a_t^2+g^2)^{1/2}$, where $a_n=\omega^2 a_1=(2\pi n/60)^2\,a_1$ is normal, $a_t=a_1\,\dot{\omega}$ is tangential, $g=9.81$ m/s^2 is Earth's acceleration, n is number of RPM, ω is angular velocity, $\dot{\omega}$ is angular acceleration, $a_1=0.408$ m is the arm length, and acceleration force $G=a/g$. When the roll angle (rotation around the x axis) equals 0 and the pitch angle (rotation around the y axis) equals 0, normal acceleration acts in the y direction and tangential acceleration acts in the x direction. Centrifugal force acts in the $-y$ direction and tangential inertial force acts in the $-x$ direction. Gravitational force acts in the z direction.

3.2 Electrical Engineering

Electrical devices (Fig. 4) used in SRM of the centrifuge consist of:

- Two EV3 Intelligent Bricks, 6 large motors, two medium motors, motor rotation sensors (embedded in motors), two colour sensors, one infrared (IR) sensor with remote IR beacon, one ultrasonic sensor – all LEGO® MINDSTORMS®;
- Slip ring 24 W from a third-party producer;
- Two slip rings 12 W from another third-party producer;
- Part of sensors from a specialized third-party producer: multi-sensor (3-axis accelerometer, compass, gyro), IR temperature sensor.

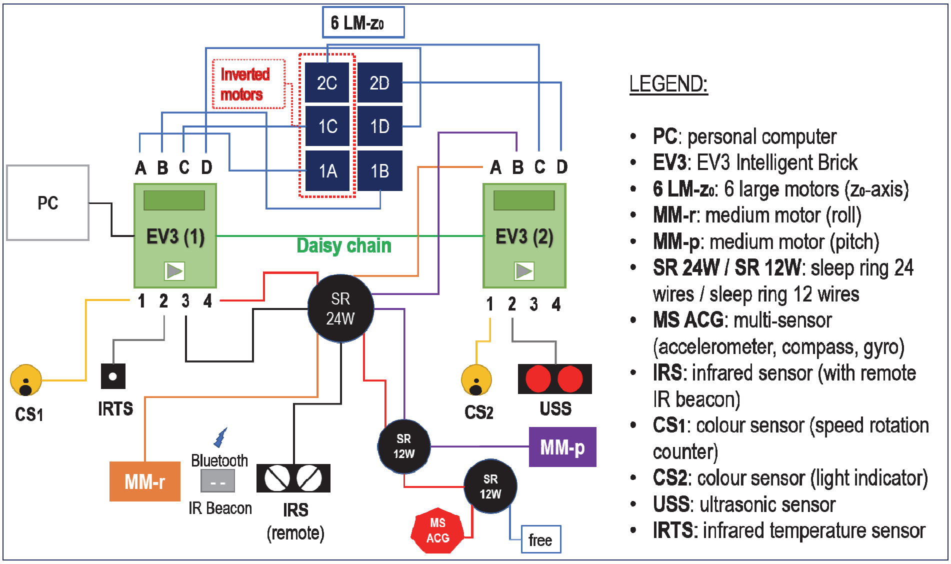
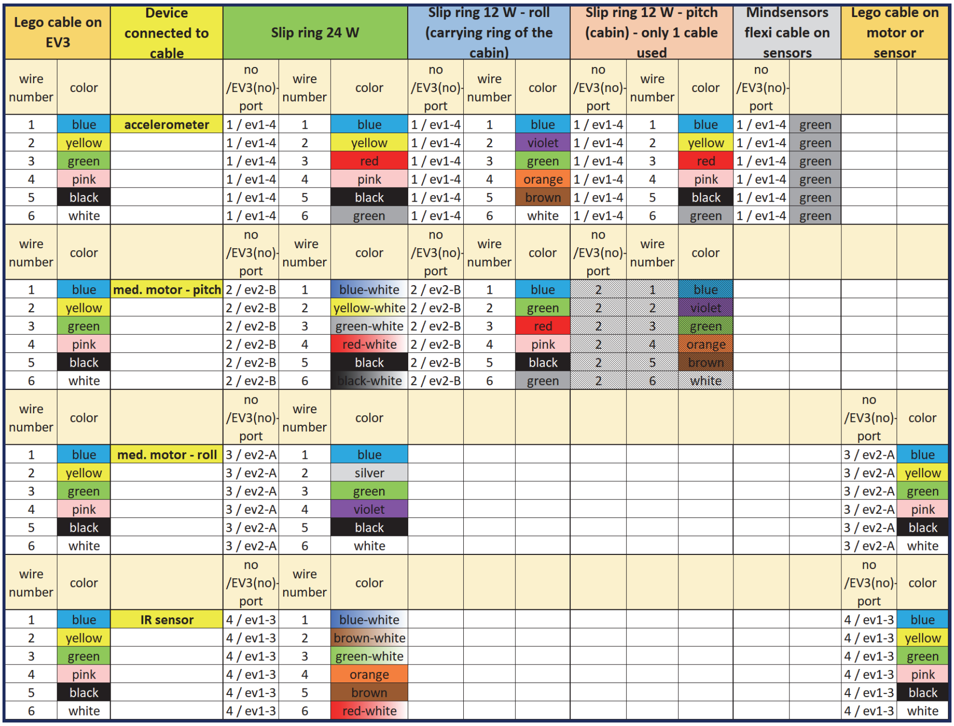


Fig. 4 – *Scheme of electrical devices connection.*



Lego cable on EV3		Device connected to cable	Slip ring 24 W			Slip ring 12 W - roll (carrying ring of the cabin)			Slip ring 12 W - pitch (cabin) - only 1 cable used			Mindsensors flexi cable on sensors		Lego cable on motor or sensor	
wire number	color		no /EV3(no)-port	wire number	color	no /EV3(no)-port	wire number	color	no /EV3(no)-port	wire number	color	no /EV3(no)-port			
1	blue	accelerometer	1 / ev1-4	1	blue	1 / ev1-4	1	blue	1 / ev1-4	1	blue	1 / ev1-4	green		
2	yellow		1 / ev1-4	2	yellow	1 / ev1-4	2	violet	1 / ev1-4	2	yellow	1 / ev1-4	green		
3	green		1 / ev1-4	3	red	1 / ev1-4	3	green	1 / ev1-4	3	red	1 / ev1-4	green		
4	pink		1 / ev1-4	4	pink	1 / ev1-4	4	orange	1 / ev1-4	4	pink	1 / ev1-4	green		
5	black		1 / ev1-4	5	black	1 / ev1-4	5	brown	1 / ev1-4	5	black	1 / ev1-4	green		
6	white		1 / ev1-4	6	green	1 / ev1-4	6	white	1 / ev1-4	6	green	1 / ev1-4	green		
wire number	color		no /EV3(no)-port	wire number	color	no /EV3(no)-port	wire number	color	no /EV3(no)-port	wire number	color				
1	blue	med. motor - pitch	2 / ev2-B	1	blue-white	2 / ev2-B	1	blue	2	1	blue				
2	yellow		2 / ev2-B	2	yellow-white	2 / ev2-B	2	green	2	2	violet				
3	green		2 / ev2-B	3	green-white	2 / ev2-B	3	red	2	3	green				
4	pink		2 / ev2-B	4	red-white	2 / ev2-B	4	pink	2	4	orange				
5	black		2 / ev2-B	5	black	2 / ev2-B	5	black	2	5	brown				
6	white		2 / ev2-B	6	black-white	2 / ev2-B	6	green	2	6	white				
wire number	color		no /EV3(no)-port	wire number	color									no /EV3(no)-port	color
1	blue	med. motor - roll	3 / ev2-A	1	blue									3 / ev2-A	blue
2	yellow		3 / ev2-A	2	silver									3 / ev2-A	yellow
3	green		3 / ev2-A	3	green									3 / ev2-A	green
4	pink		3 / ev2-A	4	violet									3 / ev2-A	pink
5	black		3 / ev2-A	5	black									3 / ev2-A	black
6	white		3 / ev2-A	6	white									3 / ev2-A	white
wire number	color		no /EV3(no)-port	wire number	color									no /EV3(no)-port	color
1	blue	IR sensor	4 / ev1-3	1	blue-white									4 / ev1-3	blue
2	yellow		4 / ev1-3	2	brown-white									4 / ev1-3	yellow
3	green		4 / ev1-3	3	green-white									4 / ev1-3	green
4	pink		4 / ev1-3	4	orange									4 / ev1-3	pink
5	black		4 / ev1-3	5	brown									4 / ev1-3	black
6	white		4 / ev1-3	6	red-white									4 / ev1-3	white

Fig. 5 – *Wire colours specification for slip ring connections.*
(Colors can be seen in electronic version)

There are eight motors and six sensors in total connected via cables to two EV3 Intelligent Bricks. The bricks are themselves connected in a daisy chain. One of them is the main one and can be connected to a personal computer (Bluetooth and Wi-Fi are other options).

Two devices are connected to EV3 Intelligent Brick through only one slip ring, the 24 W. One is connected through two slip rings 12 W, and one passes through all three slip rings.

In order to connect all devices, a combination of connection modes and a precise scheme of connecting not only cables but also individual wires within cables were necessary. To ensure the correct connection, the connection scheme for the cables that pass through the slip rings is made (Fig. 5).

Each connecting cable has 6 wires. Four cables pass through slip rings that are not LEGO products. LEGO cables and connectors are modified RJ 12 - 6/6. Fig. 6 shows cables and part of the devices prepared for mounting on the SRM physical part.

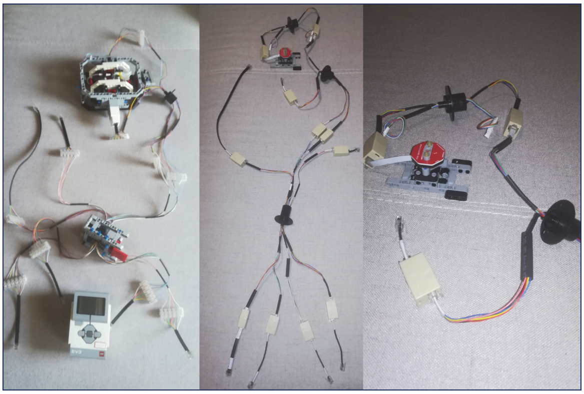


Fig. 6 – *Connecting cables and part of devices (multi-sensor is shown on the right).*

3.3 Management

Because of the existence of multiple attributes for selection among different alternatives when making decisions concerning building and using SRM of the centrifuge, several managerial procedures are provided. One of them is multi-attribute decision-making (MADM) on choosing optimal counterweight.

There are alternatives in the form of a number of steel tiles with equal mass for the variable part of the counterweight (refer to Subsection 4.1). On the basis of previous experience and the ratio of masses of the rotational parts, the following numbers of steel tiles are considered: 8, 9, 10, 11, 12, and 13.

It is necessary that the counterweight balances the mass of the arm with the cabin and its supporting ring. Distance from the centre of mass of all rotary parts to the rotation axis (z_0 -axis), r_x , can be calculated as follows:

$$r_x = (m_{ca}r_{ca} + m_g r_g - m_{cw}r_{cw})/(m_{ca} + m_g + m_{cw}), \tag{1}$$

where m_{cw} is mass of the counterweight with LEGO elements for the construction of the counterweight; m_a is mass of the arm without the counterweight; m_c is mass of the cabin with the supporting ring; r_{cw} is distance from the centre of mass of the counterweight to the z_0 -axis; r_a is distance from the centre of mass of the arm without the counterweight to the z_0 -axis; r_c is distance from the centre of mass of the cabin with the supporting ring to the z_0 -axis.

The approximate value of the moment of inertia of all rotary parts of the z_0 -axis, J_{z_0} , can be calculated as follows:

$$J_{z_0} = m_a r_a^2 + m_c r_c^2 + m_{cw} r_{cw}^2 . \tag{2}$$

The criterion for selecting the number of steel tiles is to minimize the absolute value of r_x , as well as to minimize the total moment of inertia J_{z_0} for the z_0 -axis of the centrifuge. **Table 1** shows the calculation for a different number of steel tiles.

Table 1
Calculation of r_x *and* J_{z_0} .

No of steel tiles	Mass of steel tiles [g]	m_{cw} [g]	m_a [g]	m_c [g]	r_{cw} [mm]	r_a [mm]	r_c [mm]	r_x [mm]	J_{z_0} [gmm^2]
8	812.8	1,109.8	759	453	165	75	408	25.2528	109,891,872
9	914.4	1,211.4	759	453	165	75	408	17.2766	112,657,932
10	1,016.4	1,313.0	759	453	165	75	408	9.9422	115,423,992
11	1,117.6	1,414.6	759	453	165	75	408	3.1752	118,190,052
12	1,219.2	1,516.2	759	453	165	75	408	-3.0878	120,956,112
13	1,320.8	1,617.8	759	453	165	75	408	-8.9010	123,722,172

Other relevant attributes are RPM of the z_0 -axis, vibrations, and creaking. RPM of the z_0 -axis is a measured value, while the last two attributes are rated on the 1 – 9 scale, where the best rate in the case of minimization is 9. The *G*-force is not included here because it is directly dependent on RPM. In addition, accelerometer sensitivity must be tested separately after choosing the counterweight load, as it is explained further in this paper.

Table 2

Decision on choosing optimal counterweight.

Attributes / Alternatives		RPM of z_0-axis	$\lvert r_x \rvert$ [mm]	J_{z_0} [gmm^2]	Vibrations	Creaking
N° of steel tiles	Alternative label	Type of criterion				
		max	min	min	min	min
		Weight coefficients				
		0.4	0.2	0.2	0.1	0.1
8	A1	91.8015	25.2528	109,891,872	9	2
9	A2	91.8085	17.2766	112,657,932	8	2
10	A3	91.0093	9.9422	115,423,992	4	2
11	A4	91.8645	3.1752	118,190,052	1	2
12	A5	91.7093	3.0878	120,956,112	1	1
13	A6	91.6189	8.9010	123,722,172	5	2

The alternatives are considered in **Table 2**, with selected motor power of 25% and previously defined weight coefficients for all attributes.

According to the Simple Additive Weighting method (explained in [14]), by multiplying the linearized matrix (the values of the matrix are calculated based on **Table 2**) with the vector of the weight coefficient, the following result is obtained:

$$\begin{bmatrix} 0.9993 & 0.1223 & 1.0000 & 0.1111 & 0.5000 \\ 0.9994 & 0.1787 & 0.9754 & 0.1250 & 0.5000 \\ 0.9907 & 0.3106 & 0.9521 & 0.2500 & 0.5000 \\ 1.0000 & 0.9725 & 0.9298 & 1.0000 & 0.5000 \\ 0.9983 & 1.0000 & 0.9085 & 1.0000 & 1.0000 \\ 0.9973 & 0.3469 & 0.8882 & 0.2000 & 0.5000 \end{bmatrix} \begin{bmatrix} 0.4 & 0.2 & 0.2 & 0.1 & 0.1 \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} 0.6853 \\ 0.6931 \\ 0.7238 \\ 0.9305 \\ 0.9810 \\ 0.7160 \end{bmatrix}, \quad (3)$$

which implies that the alternative A5 (12 steel tiles) is the most suitable according to the criterion of maximization.

Likewise for the counterweight, the accelerometer sensitivity should work for all expected rotational speeds. Available sensitivities are 2G, 4G, 8G, and 16G. Based on tests conducted with the chosen counterweight (11 steel tiles), it is found that the most convenient accelerometer sensitivity is 16G.

The acceleration force G components acting on the pilot's head (chest) in the simulator are: the transverse G_x component that acts from the face to the back, the lateral G_y component that acts from the pilot's right to the pilot's left side, and the longitudinal G_z component that acts from the head to the pelvis [1]. **Table 3** shows total acceleration forces in the centre of the cabin for a different number of RPM of the centrifuge arm. Measuring the total acceleration forces $G=\sqrt{G_x^2+G_y^2+G_z^2}$ by accelerometer gave similar results.

Table 3

Acceleration forces acting on the pilot head for different RPM of the centrifuge arm.

Motor power	n [RPM]	$\omega^{*)}$ [rad/s]	$G_n{}^{*)}$ [g=9.81]	$G=\sqrt{G_n^2+1}$ [g=9.81]$^{*)}$	G_y [g=9.81]	G_z [g=9.81]	G [g=9.81]
10%	36.43	3.81	-0.61	1.17	-0.66	1.01	1.21
25%	91.07	9.54	-3.78	3.91	-3.77	1.03	3.91
50%	182.14	19.07	-15.13	15.16	-17.02	1.06	17.05
75%	273.21$^{**)}$	28.61	-34.04	34.06	Not measured. It exceeds the needs of the project.		
100%	364.29$^{**)}$	38.15	-60.53	60.53			

$^{*)}$Calculated values, other values are measured

$^{**)}$Calculation based on [15] and the gear ratio

3.4 Informatics

Informatics part of this paper includes visual programming by using LEGO® MINDSTORMS® Education EV3 Software, data retrieving by using queries and connections in Microsoft Excel to process raw measurement data from the LEGO software, and making AR app in Vuforia® Studio™ which also involves creating an original Cascading Style Sheets (CSS) design.

4 Main Results and Opportunities of the Application

4.1 Physical model of the centrifuge

The physical model of the centrifuge consists of a rotary part and a static part.

The main parts of the rotary part are presented in Fig.7. There is a cabin with a supporting ring. The lower part of the cabin is exchangeable, which is suitable for performing various experiments and measurements with different sensors in the cabin. The supporting ring is important because it holds the cabin, one medium motor which drives the pitch axis, as well as one slip ring 12 W for the pitch axis, which transfers wires for the sensor in the cabin. It also holds the rotary part of the slip ring 12 W for the roll axis that transfers wires for the medium motor driving the pitch axis and a sensor in the cabin. Finally, it transmits the torque of the medium motor of the roll axis, which is fastened on the arm.

The arm is a very sturdy and robust part that carries the supporting ring with the cabin. The arm is fastened to the shaft which lies on the z_0-axis. The construction of the arm provides the approximate ratio of 1:20 (exactly 1:19.61).

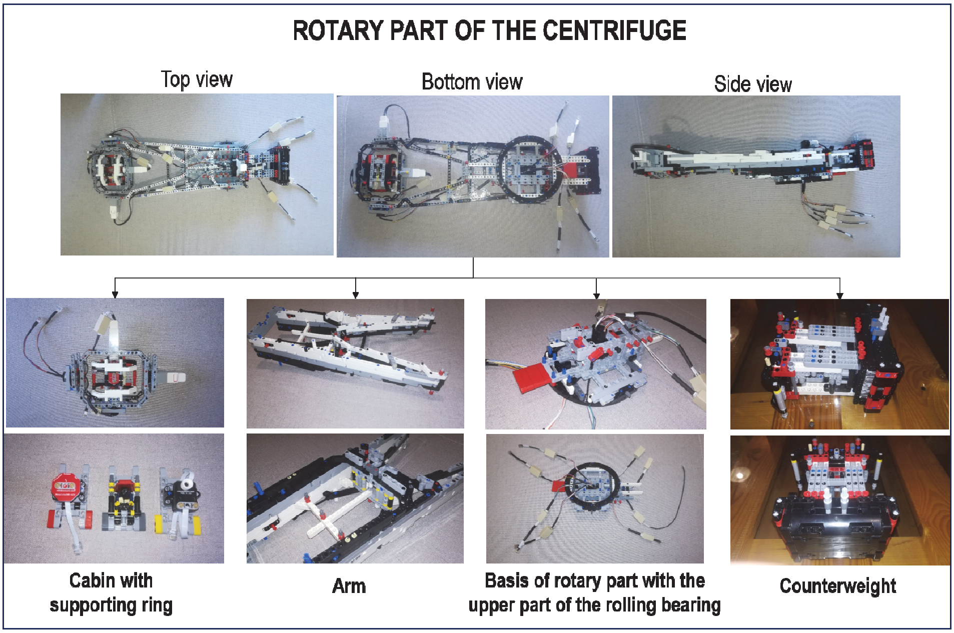


Fig. 7 – *Rotary part of the centrifuge physical model.*

The slip ring 24 W is in the middle of the basis of the rotary part with the upper part of the rolling bearing. The red extension at the back of this section is used to count the number of rotations by one of the colour sensors. For more precise measurements with high-speed rotations, multi-sensor (accelerometer, gyro) is used.

The counterweight is a very strong construction that ensures a safe and firm bond of the arm and a box that contains load made of steel tiles. The steel tiles excluded, the counterweight is made of LEGO elements and it has a mass of 297 g. Each steel tile has a mass of 100 g and is covered with a protective plastic wrap of 1.6 g. Steel tiles make the variable part of the counterweight.

The main parts of the static part of the centrifuge are presented in Fig.8.

The drive train of the z_0-axis presents a compact unit of large motors and gears (refer to Subsection 3.1).

The rolling bearing consists of the lower static part and the middle free-rotating part with a low friction coefficient that rotates between the static and the rotary part of the rolling bearing.

The presentation-development part is intended for presentation purposes (flange, differential, IR beacon storage room) and for future development. It has a roof that can be opened (must be closed before starting the rotation around the

z_0 -axis). At its roof, the ultrasonic sensor is placed, which is used for detecting movement within 255 cm and activating an alerting routine (sounds, red light, and a pitch motor rotation).

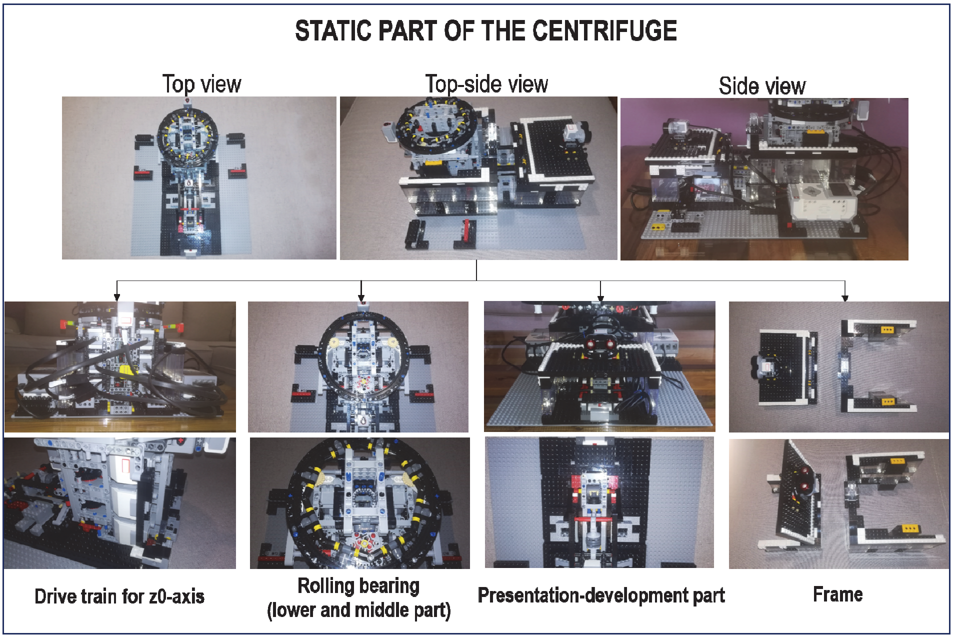


Fig. 8 – *Static part of the centrifuge physical model.*

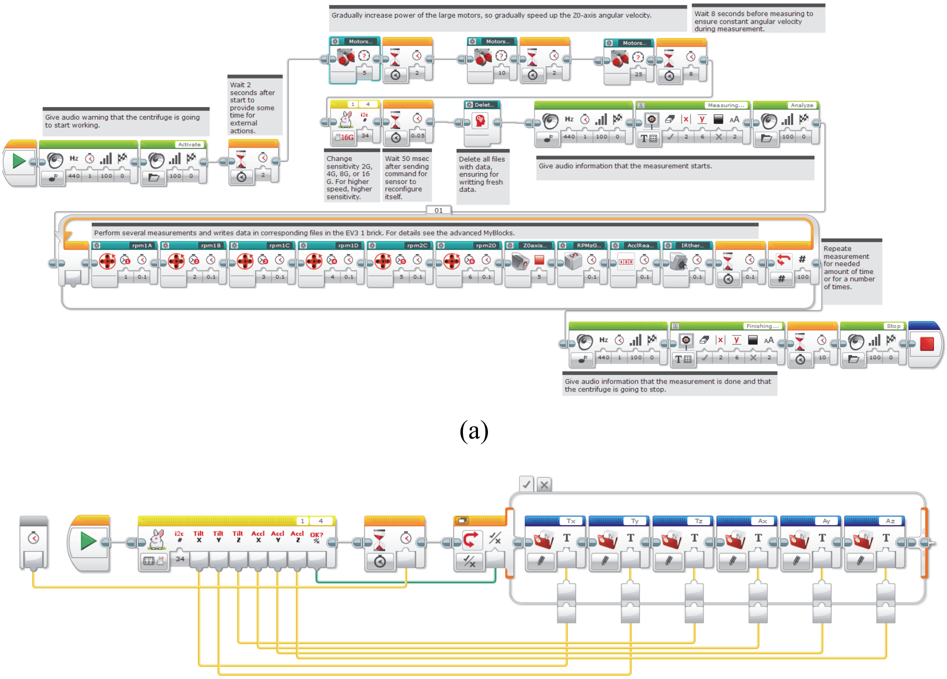
The protective presentation-supporting frame includes some transparent parts for exposition and holds one light sensor which is used as a light indicator for various purposes. It also supports the lower static part of the rolling bearing to minimize vibrations.

4.2 Software for controlling and monitoring the physical model with remote control functionality

Having in mind that the physical model is made of LEGO elements, the natural choice for a development environment was LEGO® MINDSTORMS® Education EV3 Software.

The following programs are made for different purposes in usage in the experiments with the physical model: the program for presentation of the centrifuge work with remote control functionality; the program for MADM on choosing optimal counterweight and accelerometer sensitivity depending on the rotation speed (Fig. 9a); programs for testing the physical model, motors, and sensors.

For all these programs several advanced blocks are programmed in addition to standard LEGO programming blocks. An example of the advanced block that reads measurements of acceleration and tilt in the cabin per three axes, and writes the raw data in the corresponding files, is shown in Fig. 9b.



Give audio warning that the centrifuge is going to start working.

Wait 2 seconds after start to provide some time for external actions.

Gradually increase power of the large motors, so gradually speed up the Z0-axis angular velocity.

Wait 8 seconds before measuring to ensure constant angular velocity during measurement.

Change sensitivity 2G, 4G, 8G, or 16 G. For higher speed, higher sensitivity.

Wait 50 msec after sending command for sensor to reconfigure itself.

Delete all files with data, ensuring for writting fresh data.

Give audio information that the measurement starts.

Perform several measurements and writes data in corresponding files in the EV3 1 brick. For details see the advanced MyBlocks.

Repeate measurement for needed amount of time or for a number of times.

Give audio information that the measurement is done and that the centrifuge is going to stop.

(a)

(b)

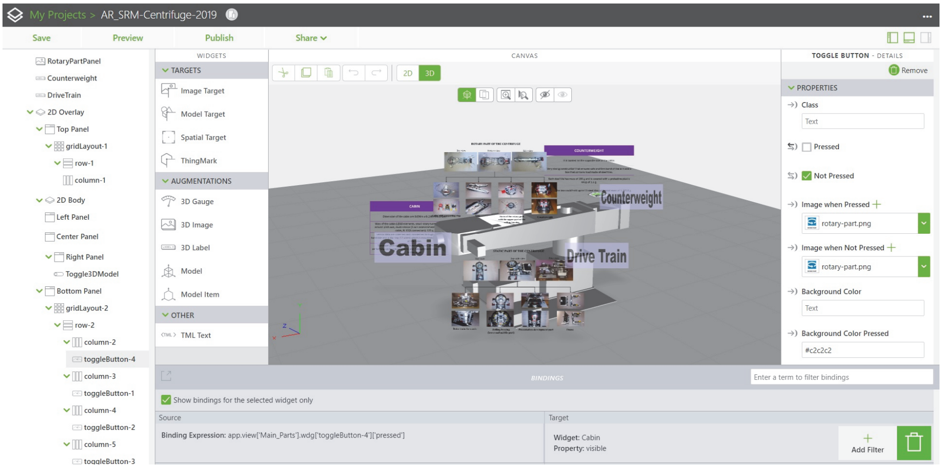
Fig. 9 – (a) *Program for MADM on choosing optimal counterweight and accelerometer sensitivity depending on rotation speed;* (b) *Example of the advanced block for acceleration and tilt measurements.*

Remote control functionality is done by making a special part of the presentation program. It is conducted using Infrared Sensor with the Remote Infrared Beacon.

4.3 AR mobile app and use of SRM in the AR mobile app

One important part of the developed SRM of the centrifuge is its presentation in the AR mobile app. The app is built in Vuforia® Studio™ (Fig.10), which uses the Cartesian coordinate system where each point has unique x, y, and z values [16].

The app is configured to be started within the mobile app Vuforia View that uses a camera to combine computer-generated graphics with video imagery (video-see through) [17]. Fig.11 shows views from the AR presentation app.



Class: Text

☐ Pressed

☑ Not Pressed

Image when Pressed: rotary-part.png

Image when Not Pressed: rotary-part.png

Background Color: Text

Background Color Pressed: #c2c2c2

Enter a term to filter bindings

☑ Show bindings for the selected widget only

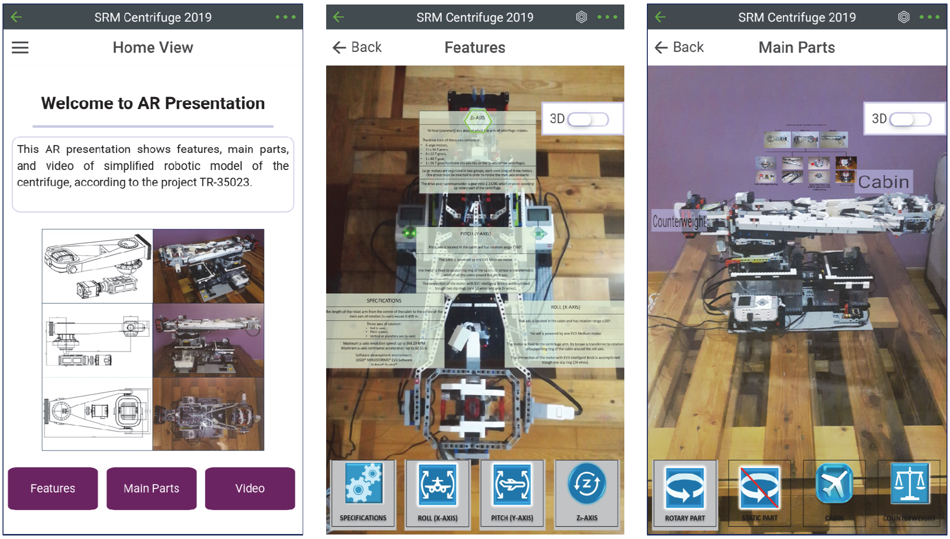
Source

Binding Expression: app.view['Main_Parts'].wdg['toggleButton-4']['pressed']

Target

Widget: Cabin
Property: visible

Fig. 10 – *Building 3D view of main parts of the centrifuge physical model in Vuforia® Studio™.*



Welcome to AR Presentation

This AR presentation shows features, main parts, and video of simplified robotic model of the centrifuge, according to the project TR-35023.

Fig. 11 – *Views in the AR presentation app: Home View, Features, Main Parts.*

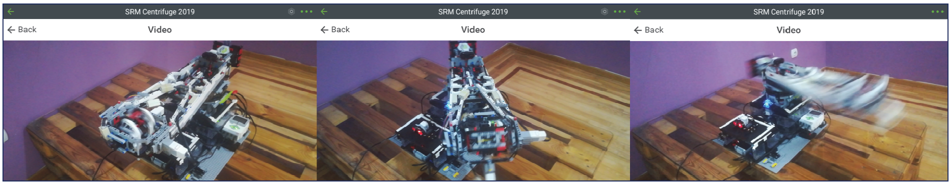


Fig. 12 – *Video View: rotation of y-axis, x-axis, and z_0-axis, respectively.*

The app also includes a video view that presents the rotation of the centrifuge for all three axes (Fig. 12).

Further development of the app includes reading and displaying the desired parameters in real time during the SRM rotation of the centrifuge based on the internet of things (IoT). AR goes well together with IoT in the sense of connectivity, mutual communication of devices in real time, and interpretation of IoT data that are superimposed over real-world objects in AR apps.

4.4. Opportunities for the application

SRM can be used as a demonstrating medium for the presentation of the project to stakeholders in different occasions (meetings, fairs, lectures) and for different purposes (introduction to the project, project promotion, learning and problem solving, fundraising).

SRM provides possibilities to test and simulate critical functionalities in a development environment without much costs and risks. Opportunity to experiment on a real model has a number of advantages over theoretical considerations of future devices, which represent a good development strategy. Also, the design and development of software and management platform are possible by using SRM.

Facilitating the understanding of engineering requirements and challenges of a project can be achieved through the use of managerial procedures and engineering calculations based on SRM. SRM allows for better planning of the project and providing a solid basis for further work. As a result, there is a reduction in the possibility of risks when making future decisions regarding expensive objects, with lessons previously learned by using SRM and transferring developed solutions with necessary modifications.

Importance of the use of SRM is emphasised with the possibility of their usage through innovative technologies (AR and IoT) that require the existence of the physical models, which can be also considered as a separated strategy.

5 Conclusion

A new concept is introduced in this paper – the concept of SRM. Its application is presented on the concrete project, TR 35023. In addition to the popularisation of knowledge in robotics, which is increasingly needed in the engineering profession, from experiments and experience in this project, it is concluded that it is possible to successfully use SRM as a strategy tool in engineering projects. Opportunities for the application of the concept are outlined. Therefore, the development of SRM of the 4-DoF disorientation device for the project TR 35023 is under consideration. The strategy of building such SRM requires knowledge from different fields and teamwork.

Because of the size of presented SRM of the centrifuge, it is not possible to provide experiments on real humans (temperature, blood pressure, electrocardiogram, electroencephalography), but it would be possible to measure the temperature on the appropriate biomaterial that has the approximate characteristics as human body (remains for future research).

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7 References

[1] R. Miller, D. Lessard: Understanding and Managing Risks in Large Engineering Projects, International Journal of Project Management, Vol. 19, No. 8, November 2001, pp. 437 – 443.

[2] Z. Dodevska, V. Kvrgić, M. Mihić: The Strategy of Building and Using Simplified Robotic Models in Engineering Projects, Proceedings of the 6th International Conference IcETRAN 2019, Silver Lake, Serbia, June 2019, pp. 69 – 70.

[3] S. Krčevinac, M. Čangalović, V. Kovačević-Vujčić, M. Matrić, M. Vujošević: Operational Research 1, Faculty of Organizational Sciences, Belgrade, Serbia, 2006. (In Serbian)

[4] A. E. Egger, A. Carpi: Modeling in Scientific Research, Visionlearning, Vol. POS-1 (8), 2008.

Available at: https://www.visionlearning.com/en/library/Process-of-Science/49/Modeling-in-Scientific-Research/153

[5] A. Quarteroni: Mathematical Models in Science and Engineering, Notice of the AMS, Vol. 56, No. 1, January 2009, pp. 10 – 19.

[6] V. K. Viswanathan, J. S. Linsey: Physical Models in Idea Generation: Hindrance or Help?, Proceedings of the 22nd International Conference on Design Theory and Methodology (DTM22), Montreal, Canada, August 2010, pp. 329 – 339.

[7] ISO 8373:2012, Robots and Robotic Devices – Vocabulary, 2nd edition, ISO – The International Organization for Standardization, Geneva, Switzerland 2012.

[8] V. Kvrgic, J. Vidakovic, M. Lutovac, G. Ferenc, V. Cvijanovic: A Control Algorithm for a Centrifuge Motion Simulator, Robotics and Computer-Integrated Manufacturing, Vol. 30, No. 4, August 2014, pp. 399 – 412.

[9] Z. A. Dodevska, V. Kvrgić, V. Štavljanin: Augmented Reality and Internet of Things – Implementation in Projects by Using Simplified Robotic Models, European Project Management Journal, Vol. 8, No. 2, December 2018, pp. 27 – 35.

[10] D. Mathias, C. Snider, B. Hicks, C. Ranscombe: Accelerating Product Prototyping through Hybrid Methods: Coupling 3D Printing and LEGO, Design Studies, Vol. 62, May 2019, pp. 68 – 99.

[11] S. Strauss, P. J. W. Woodgate, S. A. Sami, D. Heinke: Choice Reaching with a LEGO Arm Robot (CoRLEGO): The Motor System Guides Visual Attention to Movement-Relevant Information, Neural Networks, Vol. 72, December 2015, pp. 3 – 12.

[12] E. Danahy, E. Wang, J. Brockman, A. Carberry, B. Shapiro, C. B. Rogers: LEGO-Based Robotics in Higher Education: 15 Years of Student Creativity, International Journal of Advanced Robotic Systems, Vol. 11, No. 27, January 2014, pp. 1 – 15.

[13] M. Cheli, J. Sinapov, E. E. Danahy, C. Roger: Towards an Augmented Reality Framework for K-12 Robotics Education, Proceedings of the Inaugural International Workshop on Virtual, Augmented and Mixed Reality for Human-Robot Interaction (VAM-HRI'2018), Chicago, USA, March 2018, pp. 1 – 4.

[14] M. Čupić, M. Suknović: Decision Making, Faculty of Organizational Sciences, Belgrade, Serbia, 2010. (In Serbian).

[15] L. Valk: The LEGO Mindstorms EV3 Discovery Book: A Beginner's Guide to Building and Programming Robots, 1st edition, No Starch Press, San Francisco, USA, 2014.

[16] S. Aukstakalnis: Practical Augmented Reality: A Guide to the Technologies, Applications, and Human Factors for AR and VR, 2nd edition, Addison-Wesley Professional, Boston, USA, 2017.

[17] J. Peddie: Augmented Reality, Springer International Publishing AG, Cham, Switzerland, 2017.