

# 2D-Modeling with Lego Mindstorms

Miroslav Popelka, Jakub Nožička

**Abstract**—The whole work is based on possibility to use Lego Mindstorms robotics systems to reduce costs. Lego Mindstorms consists of a wide variety of hardware components necessary to simulate, programme and test of robotics systems in practice. To programme algorithm, which simulates space using the ultrasonic sensor, was used development environment supplied with kit. Software Matlab was used to render values afterwards they were measured by ultrasonic sensor. The algorithm created for this paper uses theoretical knowledge from area of signal processing. Data being processed by algorithm are collected by ultrasonic sensor that scans 2D space in front of it. Ultrasonic sensor is placed on moving arm of robot which provides horizontal moving of sensor. Vertical movement of sensor is provided by wheel drive. The robot follows map in order to get correct positioning of measured data. Based on discovered facts it is possible to consider Lego Mindstorm for low-cost and capable kit for real-time modelling.

**Keywords**—LEGO Mindstorms, ultrasonic sensor, Real-time modeling, 2D object, low-cost robotics systems, sensors, Matlab, EV3 Home Edition Software.

## I. INTRODUCTION

THE goal of this paper was to find the solution for simulating, programming and testing of robotics systems for industrial compounds, which provides saving of costs in comparison to professional industrial models. Lego Mindstorms was chosen for this goal because of meeting the requirements. Lego Mindstorms EV3 Home Edition Software, which was used to simulate to model the space, contains structural elements for easy building-up of robot itself and many sensors too. With those ones robot may orientate in the space. We needed to use especially colour sensors and distance sensors for our robot. For our purposes it was necessary to assemble the robot which uses ultrasonic sensor to model 2D space. This was solved by building the robot with ultrasonic sensor which is placed on the moving arm of robot. The moving arm of robot assures horizontal movement of sensor, vertical move of sensor is assured with wheel drive. The robot follows map in order to assure correct positioning of measured data. The sensor measures in one step data in horizontal position, in the end of step it moves sensor vertically on moving arm of robot by one step further and it measures next step. The robot follows the map in order to assure correct positioning of measured data. The map is based on system of black and white lines. Transition between white

and black line is recorded by optical sensor. When the robot comes closer to black line then the value is recorded by ultrasonic sensor. The lines are placed in a row with distance of 3 mm between each other. This is minimal possible value which sensor can record reliably. Producer of Lego Mindstorms supplies even development environment for easy programming and testing of robotics systems - LEGO MINDSTORM EV3 Home Edition. The application for moving of robot and its recording of values from sensors was created just in development environment supplied by producer. SW Matlab was selected to render values measured by sensors. The interconnection of development environment and SW Matlab supports again the fact that Lego Mindstorms is universal utility, by its using is possible to simulate, programme and test the robotics systems for industrial compounds. Still, it is possible to use another SW to reduce costs which is for free, for instance Octave [8], [9].

## II. DESCRIPTION OF HW LEGO MINDSTORM

For our work we used last version of Lego Mindstorms kit – EV3. The kit does provide a huge amount of components, engines, sensors and detectors for simulating, programming, and testing of robotics systems for industrial purpose. However, basic version did not contain sufficient amount of components for building of robot modelling 2D space. Nevertheless, the producer offers expansion kit which fits perfectly to other parts of kit. Real robotics systems use microcomputer for running of system – the same case is applied to the kit where microcomputer is so called programmable brick. Processor, operating memory and flash memory are placed in the brick. [9]

The microcomputer is controlled by Linux operating system which is additionally modified by producer for using with the kit. Our work is based on proof that it is possible to use the kit as low-cost option to create, programme and test of robotics systems in practice which is proved by assembling of robot capable of modelling 2D space. The robot is controlled by algorithm to follow map and sensors assure tracking of the map. The map consists of black and white lines and these are recorded by optical sensors placed on both sides of robot. Within the single turn of wheel the robot travels distance of 100 mm while the minimal distance between lines is 3 mm. It follows that within the single turn of wheel the robot is 2 optical sensors are capable of measuring data counting 72 values which is sufficient for modelling of space [8], [9].

## III. DESCRIPTION OF DEVELOPMENT ENVIRONMENT

We may approach with two ways how to programme assembled robotics system. The producer of Lego Mindstorms supplies even development environment with which is

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possible to programme the robot. Another option how to programme robot is programming language C# or some of other complex programming languages. Development environment supplied by producer provides completely the same options as complex programming language. As the proof, the application serves for recording values from sensors using maps created by us. This points out at cost reduction when using the kit. Development environment supplied by producer is suitable for programming practically any application. The only recommendation is to use some of complex programming language just because of saving of time to develop more complex programs. The rendering of measured data is assured by SW Matlab. The program created in environment of Matlab processes loading of collected data and their post-processing and rendering into 3D diagram. Matrix is filled up with every single scanned layer. A compiled matrix does reach size of Nx72. The number of line N depends on size of scanned object, i.e. number of scanned levels in horizontal plane. Afterwards it is possible to render scanned data in 3D diagram [4], [8].

IV. PHYSICAL BASIS FOR DISPLAYING USING BY ULTRASOUND

We may imagine ultrasound as mechanical vibration of elementary particles around their balanced states in definite environment. Ultrasound propagates in environment using energy transfer among individual elementary particles. See following equation - a part of energy coming from ultrasonic waves during mechanical vibration of elementary particles transforms into heat [5], [7]:

$$p(x) = p_0 e^{-\alpha f x}$$

where  $p(x)$  is acoustic pressure in depth  $x$ ,  
 $p_0$  is acoustic pressure on surface,  
 $\alpha$  is absorption constant,  
 $f$  is wave frequency

TABLE I  
 SPEED OF ULTRASOUND PROPAGATION IN DIFFERENT TYPES OF ENVIRONMENT

Matter	Speed of propagation (m/s)
Air	330
Water	1480
Aluminium	6400
Lead	2400

The speed of ultrasonic wave propagation depends on temperature; see Fig. 1 and it is defined according to following relation:

$$c(T) = c_0 + b \cdot (T - T_0) = c_0 \cdot [1 + b' \cdot (T - T_0)]$$

where:  $c_0$  ...speed in initial temperature  $T_0$   
 $b$  ... absolute thermal coefficient  
 $b'$  ... relative thermal coefficient

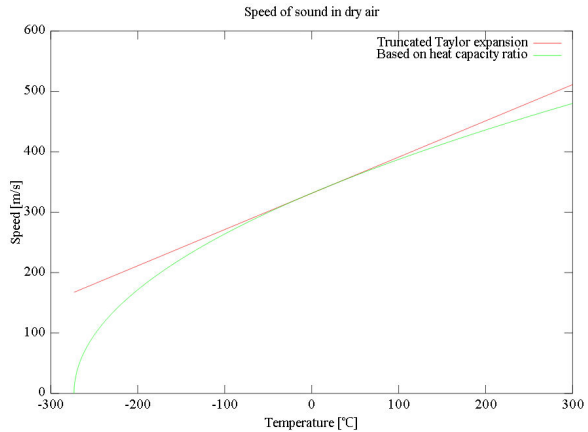


Fig. 1 Dependence of speed of ultrasonic wave propagation on temperature in the air

In case that environment for waves propagating is the air, so speed is approximately 345 m/s, see Table I. Changes in temperature cause not only changes of sound speed, but even material's characteristics used in ultrasonic sensor. Running of sensors in significantly higher or lower temperatures leads to shift their resonance frequency and it follows further to decreased sensitivity. Decreasing sensitivity does not represent problem for most applications, however application requiring high range of working temperatures may require constructional modifications [5], [6].

During changes of conditions in which acoustic waves propagate, for instance changes in temperature, air humidity or air pressure, it causes changes in speed of sound propagation and it represents source of errors in measurement. In the following Fig. 2 there is displayed attenuation as function of temperature, air humidity and air pressure [5], [6].

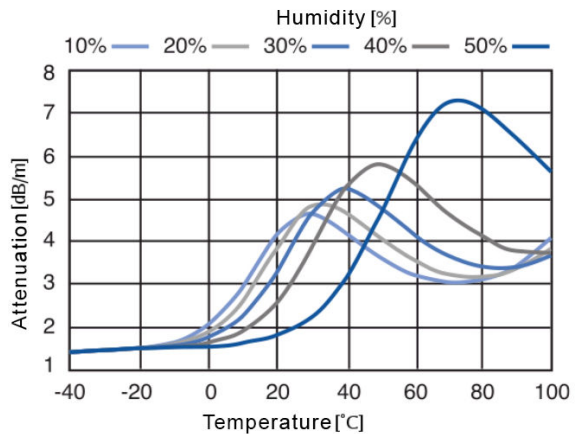


Fig. 2 Attenuation counting 100kHz in pressure of 1 atmosphere

A. Wave Length

The size of wave length determines definition or the smallest distance among detected objects, see Table II [3], [5].

TABLE II  
DEPENDENCE OF WAVE LENGTH ON FREQUENCY AND ENVIRONMENT

Environment	Sound speed [ms <sup>-1</sup> ]	Wavelength λ [mm] for each frequency			
		20 kHz	40 kHz	100 kHz	200 kHz
Carbon dioxide (25°C)	259	22,95	6,48	2,59	1,3
Oxygen (25°C)	316	15,8	7,9	3,16	1,58
Dry air (0°C)	331,4	16,57	8,29	3,31	1,66
Dry air (25°C)	346,3	17,32	8,66	3,46	1,73
Helium (0°C)	970	48,5	24,25	9,7	4,85
Hydrogen (25°C)	1270	63,5	31,75	12,7	6,35
Distilled water (25°C)	1497	74,87	37,43	14,97	7,49
Sea water (13°C)	1500	75	37,5	15	7,5
Ice (-4°C)	3250	162,5	81,25	32,5	16,25
Glass (20°C)	5200	260	130	52	26
Iron (20°C) lengthwise	5900	295	147,5	59	29,5
Iron (20°C) transversely	3200	160	80	32	16

*B. Acoustic Impedance*

Acoustic impedance is product of density and sound propagation speed [3], [5]:

$$Z = c \cdot \rho$$

Value of air Z: 0,44 kPa.s.m<sup>-1</sup>.

TABLE III  
ENVIRONMENT DENSITY

Matter	Density kg.m <sup>-3</sup>
Nitrogen	1,234
Oxygen	1,409
Earth	5 515
Zinc	7 140
Gold	19 320
Iron	7 870
Granite	2 600-2 900
Brick	1 800-2 400
Concrete	2 300-2 400

Acoustic impedance is individual for each environment, see Table III. This is resistance endured the passage of ultrasonic waves through the environment. Total loss of energy which is caused by absorption of energy in homogeneous environment is called attenuation. See Figs. 3 and 4 [5].

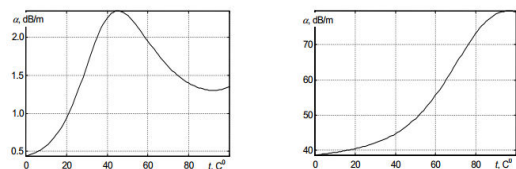


Fig. 3 Dependence of ultrasonic coefficient of absorption on temperature at frequency 50 kHz and 100 kHz at pressure 105 Pa and relative humidity 60 %

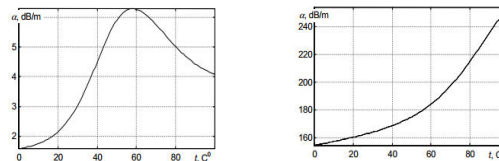


Fig. 4 Dependence of ultrasonic coefficient of absorption on temperature at frequency 500 kHz and 1000 kHz at pressure 105 Pa and relative humidity 60 %

*C. Reflection and Refraction*

Beam goes through partly to second environment and partly reflects back on falling on dividing line of two environments having different impedance. In case of transition happens to refraction only if the size of obstruction is larger than wave length of ultrasonic waves. If wave length is the same, so it gets bent [1], [3], [5].

Reflection and refraction are defined by following mathematical laws:

Reflection and refraction law

$$\alpha_1 = \alpha_2$$

Refraction law:

$$\sin \alpha_2 = c_2 / c_1 \sin \alpha_1$$

where  $\alpha_1$  is angle of descent on dividing line  
 $\alpha_2$  je angle of reflection from dividing line  
 $\alpha_3$  is angle under which sent wave passed through dividing line

*D. Wave Intensity*

On propagating of ultrasonic wave it gets to transition of energy among particles. The energy propagates at constant speed as waves. Therefore it is possible to define wave intensity as median of energy going through at time through surface perpendicular to direction of propagation of ultrasonic wave. [5]-[7].

V. TYPES OF ULTRASONIC SCREENING

*A. Method A*

The basic type of ultrasonic screening is method A (A-scan, amplitude modulation). It is case of single dimension technology using only one sensor to assemble screen, see Fig. 5. This method is based on recognition of reflected echo in received signal. It uses two factors: we count difference of sending time and reception of ultrasonic wave and afterwards it is subtracted the size of amplitude from it. Size of amplitude is corresponding with energy of reflected wave. From this information we establish final image displayed in the Fig 5 [1], [6].

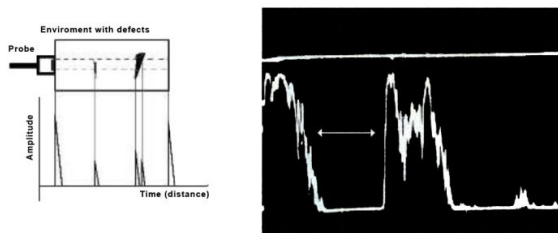


Fig. 5 Ultrasonic imaging method A

**B. Method B**

Method B, meant as “B”(brightness modulation), has become developmental step of ultrasonic diagnostic methods. The basic principle is grounded in matching to gained size of echo amplitude within method A, specific value of brightness, see Fig. 6. [1], [6]

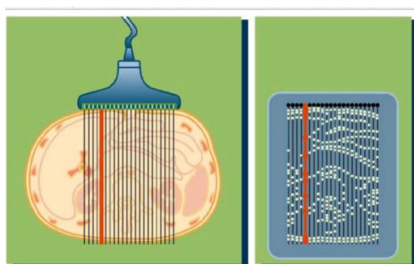


Fig. 6 Princip of method B

In development it appeared another option of method, so called two-dimensional. The two-dimensional method B uses in general principle arrangement of more sensors which may deliver complete 2D image, see Fig. 7 [1], [5], [6]



Fig. 7 Example of ultrasonic imaging method B

Two-dimensional method B was further improved using by panoramic and harmonical imaging.

**1. Panoramic Imaging**

Enables to gain consistent visual information and after scanning all required areas it is possible to establish Figure with significantly better parameters.

**2. Harmonical Imaging**

Improves the quality of final image by enhancing of radiation patterns. A technique for the extended goal calls Beamforming and it is being used for modification of the main radiation lobe of radiation pattern [1], [5], [6].

**C. Method M, TM**

Method uses one-dimensional method B to display motion of displayed objects. Repetitive scanning of the same space is used to display that motion and so we receive information about moving object. That is why this method got title M-mode (motion), see Fig. 8 [2], [6].

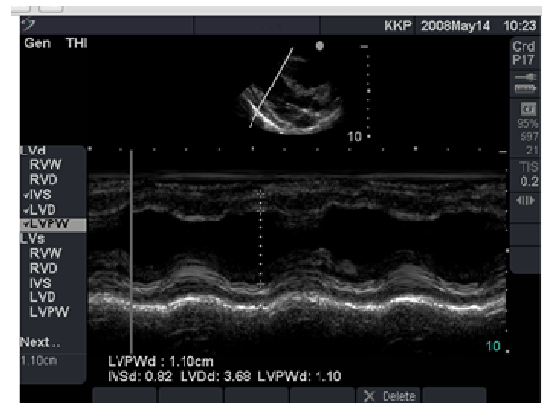


Fig. 8 Ultrasonic imaging method M

**D. 3D Projection**

Thanks to development and technology of increasing the hardware performance it happened to develop method of 3D projection. 3D image is being collected thanks to moving of two-dimensional detector and by ordering collected data into sequence, in which they create just required 3D image, see Fig. 9 [1], [5].

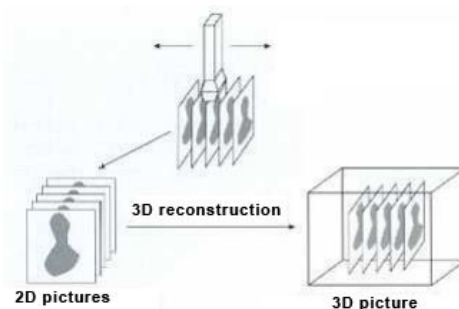


Fig. 9 3D reconstruction of 2D pictures

**E. Methods Based On Doppler Effect**

For purposes of detection of moving object is used Doppler effect. It is describing behaviour of acoustic waves during moving of source of acoustic waves regarding to reference point (e.g. passing train) [5].

In case of oncoming source of waves, the frequency of emitted waves appears as higher and lower during receding. It happens the same effect when it is happening only reflection

from moving obstacle. Doppler Effect, see Fig. 10, is described by following equation:

$$fd = \frac{2f_v \cdot \cos \alpha}{c}$$

where:

v is speed of obstacle

c is speed of propagation sound in particular environment

$\alpha$  is doppler angle, i.e. angle between falling waves on moving object and vector of direction of its motion [5], [6].

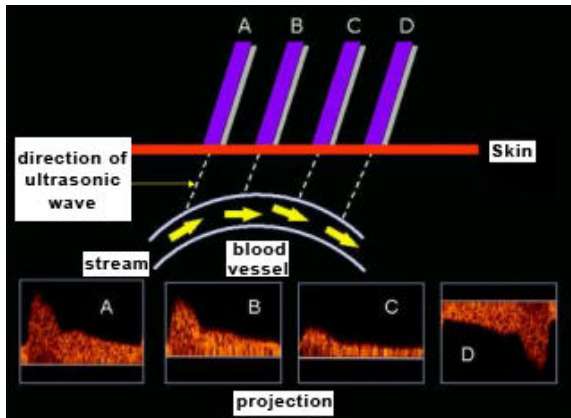


Fig. 10 Ultrasonic imaging with Doppler effect

According to way of evaluation and processing of sent and reflected waves there are used two methods

- With unmodulated carrier wave (CW)
- With pulse modulated carrier wave (PW)

#### 1. With Unmodulated Carrier Wave (CWD)

This system, see Fig. 11, which works with two ultrasonic sensors, where first is transmitter and second receiver. They form obtuse angle because of overlap in so called sensitive region. In case of presence of more moving objects in sensitive region it is not possible to determine correctly the speed of particular object using by this method, because there is no information about third dimension. On the other hand high accuracy of speed measuring of single object counts as advantage.

#### 2. With Pulse Modulated Carrier Wave (PWD)

This system is created by combining of emitting ultrasonic pulses with speed measuring at period of time defined using by emitted and reflected ultrasonic pulses, see Fig. 10 [2], [5].

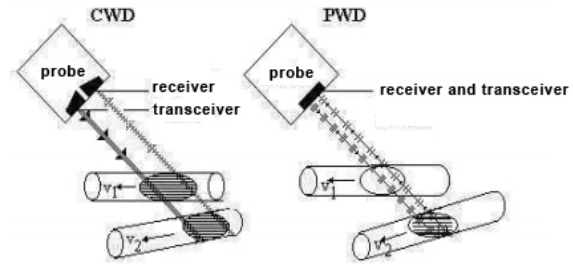


Fig. 11 Example of CWD and PWD methods

## VI. DESCRIPTION OF SIMULATED PROCESS

There is described system, see Fig. 12 that serves to simulate space using by Lego Mindstorms kit. The robotics system consists wheel drive and lift arm. Scanning elements, sensors of colour, according which the whole robotics system orientates in the space, are placed alongside of wheel drive. Ultrasonic sensor is placed on lifting arm in order to reach two degrees of freedom for simulating of space. The robotics assembly moves using by black and white map, consist of set of black lines with the same distance. Sensors of colour scan during the moving of the whole robotics system location of black lines on white surface and that enables to scan data in regular interval measured by ultrasonic sensor.

The behaviour of robot and collecting data is programmed in environment of Lego Mindstorms Home edition which is freely available on website of producer. Environment of Matlab / C# enables to process collected data.

#### A. Motion Principle a Collecting Data

Moving of robotics assembly is driven using by created program in freely available development environment of Lego Mindstorms Home edition. Following Fig. 12 shows a part of the whole robotics system in order to get complete 2D image of scanned object.

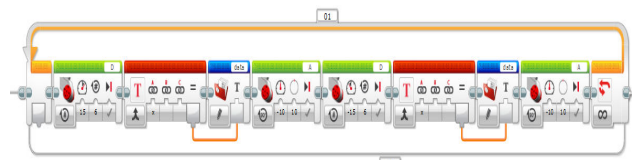


Fig. 12 Part of source code for scanning

Collecting data necessary for modelling of 2D model runs in precisely defined moments, dependent on distance of scanned black lines.

#### B. Software for Processing of Collected Data

The collected data are processed and rendered into 3D diagram in Matlab environment. There were scanned three objects in development and results were processed and projected. A demonstration of code for projecting of scanned data in Matlab environment, see:

```
layer=data(prev_count+1:counter-1);
layer = layer (layer <20);
```

```
layer1= layer (1:floor(length(layer)/2));
layer2= layer (floor(length(layer)/2)+1:end);
```

```
result(i,middle-length(layer1)+1:middle)= layer1;
result(i,middle+1:middle+1+length(layer2)-1)= layer2;
```

### 1. Object no.1. Cube

Object in shape of cube was placed in front of scanning robotics system. Edge length is 9.5cm. Received results during scanning are mentioned in the Fig. 13. Moreover, there is showed photograph of real scanned cube in the Fig. 14.

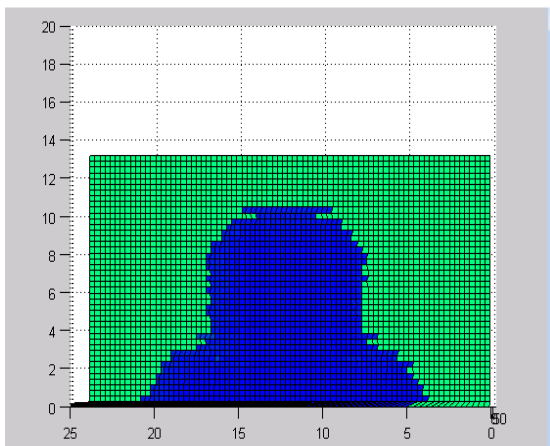


Fig. 13 Measured data from ultrasonic sensor (Cube)

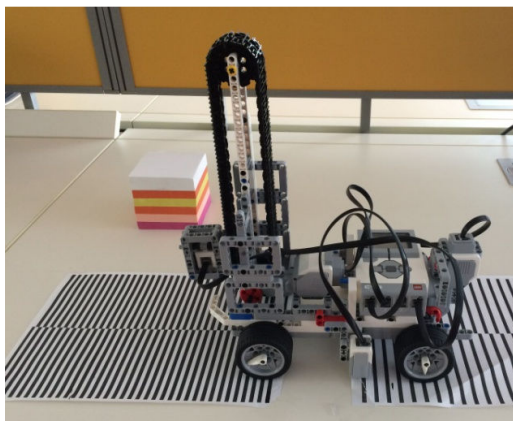


Fig. 14 Real scanned cube

### 2. Object no.2. Cylinder

After that, object in shape of cylinder was placed in front of sensor. The cylinder was 10 cm high and its radius base measured 4.5 cm. Received results during scanning and real referential object are displayed in the Figs. 15 and 16.

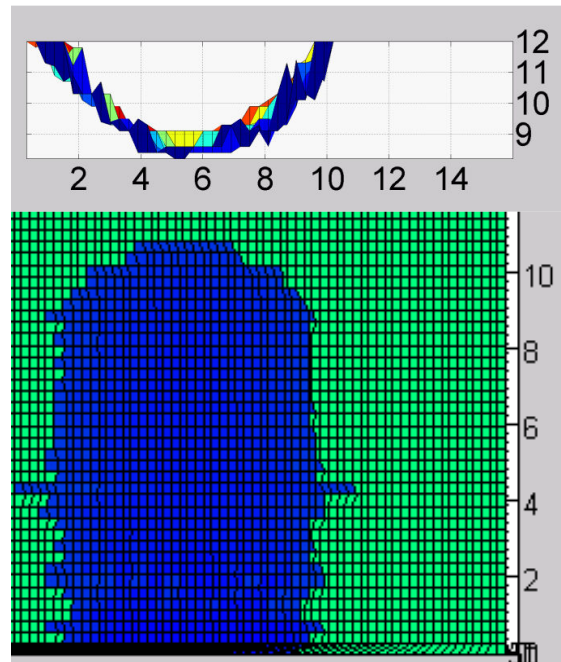


Fig. 15 Measured data from ultrasonic sensor (Cylinder)

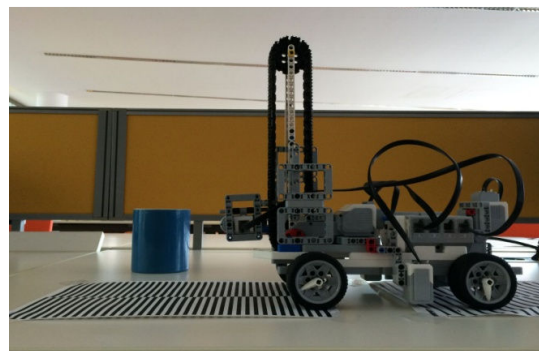


Fig. 16 Real scanned cylinder (coffee mug)

### 3. Object no.3. Circle

Circle was scanned in the following step to recognize capabilities of ultrasonic sensor. Speaking of geometrical aspects, it is still case of cylinder, but in this case height was irrelevant.

Ultrasonic sensor scanned circular surface with radius 9.5 cm, see Fig. 17. And there is real scanned object in the Fig. 18.

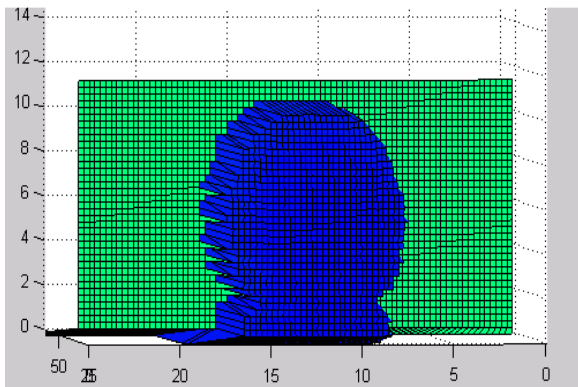


Fig. 17 Measured data from ultrasonic sensor (Circle)

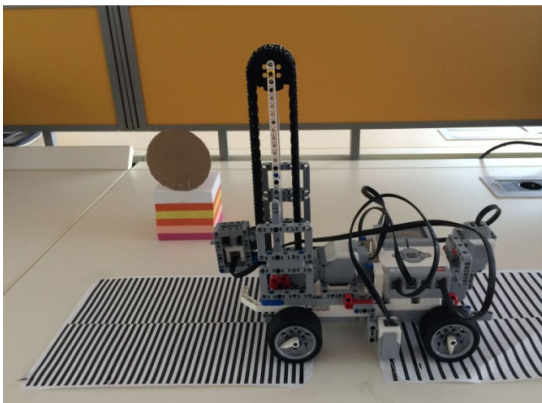


Fig. 18 Real scanned circle (paper circle)

## VII. CONCLUSION

In this paper we examined in detail options of simulation of robotics systems using by Lego Mindstorms kit. As the main reason to use the kit in simulations of robotics systems is possibility to model, programme and test robotics systems for industrial compounds. In addition, as the central reason is its easy availability providing simulations of robotics systems with minimal costs of production compared to professional kits for simulations with aim to sustain the same options and functions. We proved by this work that using Lego Mindstorms kit leads to optimizing solution, increasing of efficiency and reduction of costs. We defined possible physical projection of space using by ultrasound and feasible types of projecting using by ultrasonic sensors. In order to verify features of ultrasonic sensors there were chosen 3 basic geometrical figures: cube, cylinder, circle. After scanning and processing the whole object it was constructed 2D model of scanned space.

By designing of 2D simulation we proved that the kit can be consider for quality and simultaneously low-cost utility for simulations of robotics systems.

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