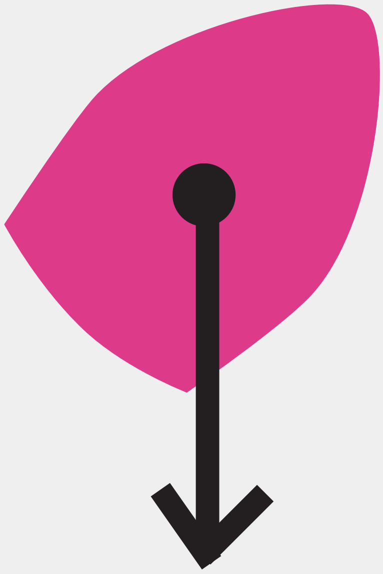

Physics Report

The application of physics in a typical ID project

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Abstract

In this report I show the application of knowledge I gained in the basic course physics in my design project of the first semester: ekk Bounce. I do that by solving a number of problems, such as calculating the battery life of the system, the intensity of the lights in the object and the forces exerted on the product when it is dropped on the ground.

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Introduction

This report is about a number of problems involving physics in a typical Industrial Design project. I took this quite literally, by applying the knowledge I learnt in the basic course Physics to analyze the design project I worked on during the first semester: ekk Bounce.

Context

The aim of this product is to stimulate children in the first grades of primary school (aged 4 to 6 years) to share toys instead of having an argument about who can play with a toy. By using this product children will be able to solve these kinds of problems themselves without the intervention of the teacher. As a result the teacher is less distracted and can spend more time on actual teaching.

Two pupils using ekk Bounce

The product consists of two parts: a system that works on a PC in the classroom and devices that are called 'ekks'. Each pupil has its own ekk. When they want to play with a toy, they 'tap' their ekk on the toy and the ekk will light up blue. If another child does the same, both ekks will give a signal: the kids need to battle by bouncing their ekks against each other. The devices will then connect to the system to decide which child can play with the toy and light up green, or red. It is also possible that the system decides that the kids should play together. In this case both ekks will light up green. The decisions by the system are based on a chance model that uses the activities that a child did before and specific settings entered by the teacher.

This report focuses on the prototype of the hardware of Ekk bounce, the ekks. The prototype is a 3D-printed object which contains an Arduino Uno microcontroller, an rgb-LED, a RFID-reader and a 9V battery.

Research questions

In this report I'd like to answer four research questions:

- What is the intensity of the lights from the perspective of a user?
- Which resistors do I need for the circuit to work properly?
- What is the battery life of the prototype?
- Will the outer shell of the device normal use and a fall to the ground?

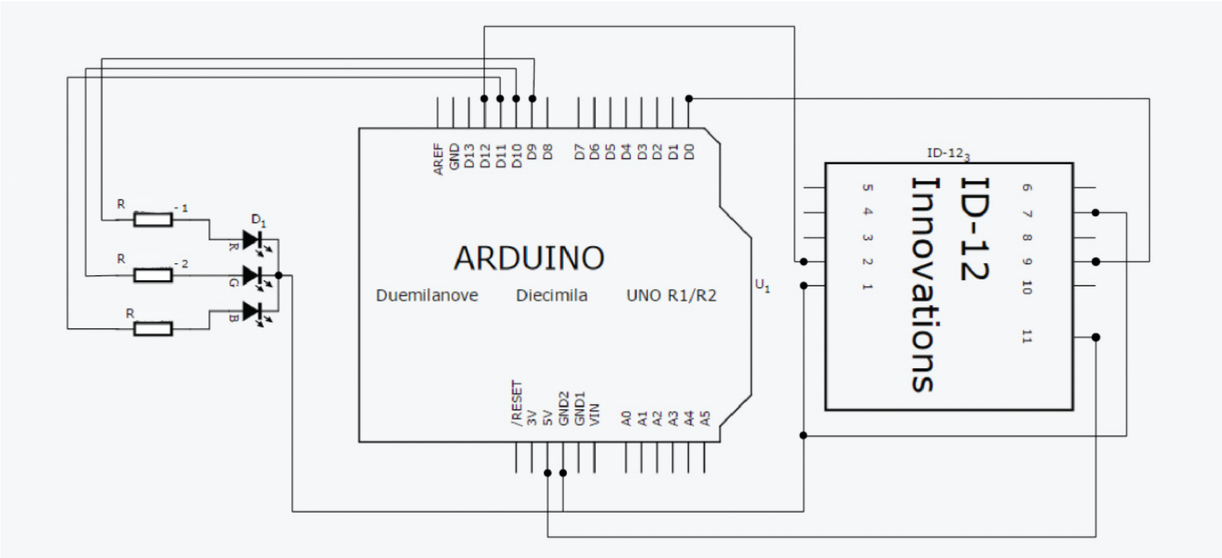
Resistors & intensity

To make sure the rgb-LED lasts long and works as expected, I need to use some resistors in the circuit for current limiting. The voltage of the Arduino digital output ports that control and power the LED's is 5.0 V. According to the datasheet of the rgb-LED that I use, the lights have these forward voltages when I_f = 20 mA:

$V_{f\text{-red}}$ = 2.0 V
$V_{f\text{-green}}$ = 3.2 V
$V_{f\text{-blue}}$ = 3.2 V

$$R_{red} = \frac{Vs - Vf\text{-}red}{I} = \frac{5.0\ V - 2.0\ V}{20\ mA} = 150\ \Omega$$

$$R_{green} = R_{blue} = \frac{Vs - Vf\text{-}green/blue}{I} = \frac{5.0\ V\ - 3.2\ V}{20\ mA} = 90\ \Omega$$



The circuit of the prototype

The resistor limits the currents and uses a certain amount of power. I can calculate the power rating I need for the resistors in my circuit. According to Kirchhoffs voltage Law the following yields:

V_{source} - (voltage drop LED) - (voltage drop resistor) = 0

$V_{R\text{-red}}$ = Vsource - (voltage drop LED) = 5.0 V - 2.0 V = 3.0 V
$V_{R\text{-green/blue}}$ = Vsource - (voltage drop LED) = 5.0 V - 3.2 V = 1.8 V

P_R = $V_R \times I = I2 \times R = V_R^2 / R$
$P_{R\text{-red}}$ = $V_{R\text{-red}}^2 / R = (3.0\ V)^2 / 150\ \Omega = 60\ mW$
$P_{R\text{-green/blue}}$ = $V_{R\text{-green/blue}}^2 / R = (1.8\ V)^2 / 90\ \Omega = 36\ mW$

Based on these calculations I need to use one 150 Ω resistor and two 90 Ω resistors. The power into these components is either 60 mW or 36 mW. Standard resistors come with a power rating of 0.25 W or 0.50 W[I] . This means I don't need to look for special high-power resistors.

Intensity
Knowing the power of each color LED in the light, I can calculate the intensity of the light at a certain distance. For this example I want to know the intensity at a distance of 1m.

$P_{R\text{-red}}$: 60 mW
$P_{R\text{-green/blue}}$: 36 mW
$P_{R\text{-white}}$: (60+36+36) mW = 132 mW
d : 1.0 m
viewing angle θ : 120° = 2.0943951 rad
A[II] : $2r^2 \times \theta$

$$I = \frac{P}{A} = \frac{P}{2r^2 \times \theta}$$
$$I_{red} = \frac{P}{A} = \frac{P}{2r^2 \times \theta} = \frac{60\ mW}{2 \times 1m \times 2.0943951\ \text{rad}} = 14.32\ mW$$
$$I_{green/blue} = \frac{P}{A} = \frac{P}{2r^2 \times \theta} = \frac{36\ mW}{2 \times 1m \times 2.0943951\ \text{rad}} = 8.59\ mW$$
$$I_{white} = \frac{P}{A} = \frac{P}{2r^2 \times \theta} = \frac{132\ mW}{2 \times 1m \times 2.0943951\ \text{rad}} = 31.51\ mW$$

I see that the intensity of the lights from a user perspective varies from 14.32 mW to 31.51 mW depending on the color. The intensity is the highest for the color white, because this color is made by powering all LED's at the same time.

I Sparkfun, 2015
II Wolfram Mathworld

Energy consumption

Another thing I want to know is how long the system works on a single battery. In short term it is handy to know how many batteries I need to buy to make sure the product works during the demodays. In the long term it gives insight in how the system could be made more power efficient in a new prototype or a final product.

Two components work continuously, the Arduino microcontroller and the RFID reader. By calculating their energy use I can get an idea of the use in 'stand-by mode'. The Arduino is powered by a standard 9.0V battery and the RFID reader draws its power from the Arduino board. A linear power regulator in the Arduino will convert the voltage of the battery to 5.0 V. The remaining 4.0V will be waste heat.

Based on the datasheets and measurements on power consumption by other users I assume these characteristics for the components:

ID-12 RFID reader	: 5.0V at 35mA
Arduino Uno	: 9.0V at 40mA
Energizer 9.0V battery	: 500mAh at a constant current draw of 100mA

The total amount of current that the Arduino draws from the battery:
$I_{rfid}+I_{arduino}$= 35 mA + 40 mA = 75 mA

The runtime of the system in stand-by mode on a single 9V battery would be:
T=(Capacity battery)/(I-system)=500mAh/75mA=6.67 hours.

If the system reads a known RFID-tag, it will power the rgb-led. On average the current draw will increase for ten seconds: Five seconds to turn blue and another five seconds for the battle action where the LED fades white, red, or green. I assume that the average current during these 10 seconds will be 20mA. The voltage of the current is 5.0 V, because that is the default voltage of the digital output port of an Arduino.

When the system is working continuously, the battery life would be:
T=(Capacity battery)/(I_{system} + I_{ports})=500mAh/95mA=5.26 hours

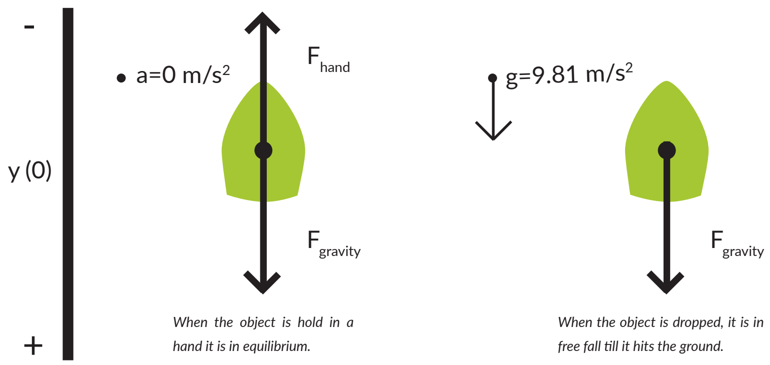
So the system will work 5.26 hours to 6.67 hours on a single 9V battery, depending on its use. That is sufficient for one demoday. The efficiency of the system could be easily improved though. A method could be the use of a battery of a voltage that is more nearby to the 5V that is used by the Arduino. Now a lot of energy ends up as waste heat in the power regulator. Another method to decrease the energy consumption is to make use of the sleep function of the Arduino in the program to save some energy in stand-by mode (In sleep mode the board draws a current of 10-30mA instead of 40mA).

Durability

To see if the material of the 3D printed shell of the ekk can withstand all the forces that work on the object, I need to calculate the forces and energy in two situations: A child accidentally drops the ekk on the ground. The second situation is a battle between to ekk Bounce users, which is essentially a collision of two bodies.

When I know the potential energy, I can find the end speed when the object hits the ground. After finding the end speed I am able to find the average force of impact when I know the distance traveled by the ekk after it has hit the ground.
I need to set up some information to calculate the potential energy of the ekk if a child holds it, namely the mass of the object, the gravitation constant and the height of the hands that hold the object.

$m_{arduino}$: 28 g
$m_{battery}$: 45 g
m_{RFID} : 10 g
m_{ABS} : 30 g
m_{misc} : 5 g
g : 9.81 m/s2
h : 0.825 m[III]



$$E_g = M_{total} \times g \times h = (28+45+10+30+5)\text{kg} \times 10^{-3} \times 9.81\ \text{m/s}^2 \times 0.825\text{m} = 0.95\ \text{J}$$

When the object is dropped E_g will be transformed into kinetic energy E_k. Neglecting the effects of air friction, I can find the end speed by using this formula:

$$E_g = E_k = \tfrac{1}{2} m \times v^2$$

$$v_{drop} = \sqrt{\frac{2 \times E_k}{m}} = \sqrt{\frac{2 \times 0.95 J}{0.118\ kg}} = 4.0126\ \text{m/s} = 4.0\ \text{m/s}$$

I can find the average force of impact with the Work-energy principle. To use this principle I need to know the distance traveled after impact (The object bounces to a certain height after it hits the ground). I expect this distance to be 10 cm.

d : 0.1 m
V_{drop} : 4.0 m/s
V_{final} : 0.0 m/s

III This is based on the assumption that the hands are at a height of ¾ the length of a child when it holds an object. The length is based on the growth curve of the WHO (2014) which shows an average length of 110 cm for a 5-year old boy.

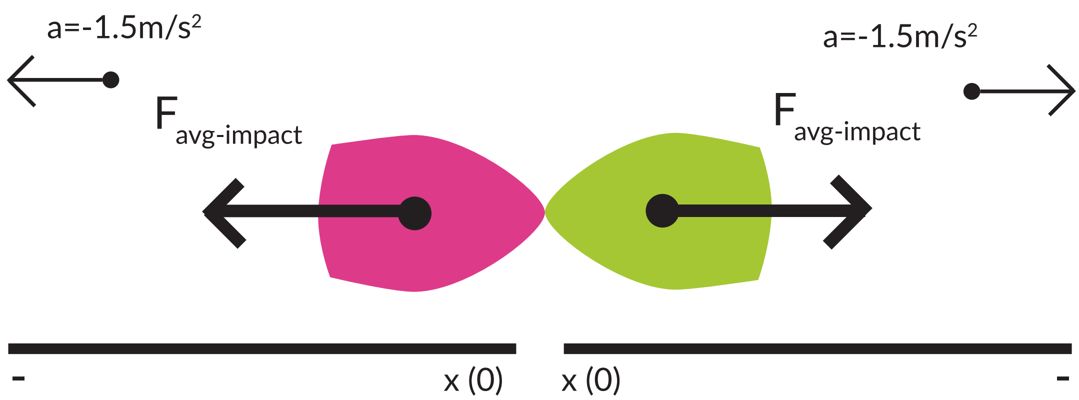
$$W_{net} = ½ \text{ m} \times V_{final}^2 - ½ \text{ m} \times V_{drop}^2 = F_{avg\text{-}impact} \times d$$

$$F_{avg\text{-}impact} = \frac{½ \text{ m} \times V_{final}^2 - ½ \text{ m} \times V_{drop}^2}{d} = \frac{-½ \times 0.118 \text{ kg} \times (4.0\ m/s)^2}{0.1\ m} = -9.44 \text{ N} = -9.4 \text{ N}$$

In the formula the force is negative, because it works in a direction opposite to the initial movement. The average force of impact after a fall is therefore 9.4 N.
The average force of impact of a collision between two ekks in a battle can be calculated with another method: The formula for impulse of force which is derived from Newton's second law.

$$\text{Impulse} = F_{avg\text{-}impact} \times \Delta t = m \times \Delta v$$

I know the mass of the ekk from previous calculations. The time and speeds of the collision are retrievable by looking at the demonstration video[IV] of ekk Bounce .



Two free body diagrams of the ekks at the moment of collision

m : 0.118 kg
Δt : 0.25 s
v_{start} : 1 m/s
v_{end} : -0.5 m/s

$$F_{avg\text{-}impact} = \frac{m \times \Delta v}{\Delta t} = \frac{0.118 \text{ kg} \times (-0.5-1) m/s}{0.25 s} = -0.708 \text{ N} = -0.7 \text{ N}$$

As in the previous situation the force is negative, because it works in a direction opposite to the initial movement. The average force of impact in this collision is therefore 0.7 N.

The impact strength of plastics can be measured with the Izod impact test. This test shows the lost energy per unit thickness of a material. The impact strength for the material used for the ekk, ABS, is 4.36 J/cm.

IV ekk Bounce, https://www.youtube.com/watch?v=A3N-jtY-Ew0

I can find the lost energy of the two collisions that I analyzed by computing the impulse and divide it by the thickness of the outer shell of an ekk.

m : 0.118 kg
Δv_{drop} : 4.0 m/s
Δv_{bounce} : 1.5 m/s
Thickness : 0.3 cm

$$Impulse_{drop} = m \times \Delta v_{drop} = 0.118\ kg \times 4.0\ m/s = 0.472\ J$$

$$\text{Impact per unit thickness} = \frac{Impulse}{thickness} = \frac{0.472\ J}{0.3\ cm} = 1.57333\ J/cm = 1.57\ J/cm$$

$$Impulse_{bounce} = m \times \Delta v_{bounce} = 0.118\ kg \times 1.5 m/s = 0.177\ J$$

$$\text{Impact per unit thickness} = \frac{Impulse}{thickness} = \frac{0.177\ J}{0.3\ cm} = 0.59\ J/cm$$

Ignoring the influence of the construction of the shell of the device, the material ABS is strong enough to survive a collision with another object while it is in use and it won't break if a user drops the object accidentally.

Conclusions & reflection

In the introduction I formulated four research questions. Thanks to the things I learned in the course Physics I was able to answer them all (to some extent). First, the intensity of the lights from a user perspective varies from 14.32 mW to 31.51 mW depending on the color. The intensity is the highest for the color white, because this color is made by powering all LED's at the same time. To make sure the LED's in the circuit work properly, I need to use a 150Ω resistor for the red LED. For both the green and blue LED I have to use a 90Ω resistor.

The battery life of the prototype when powered by a 9V battery varies between 5.25 hours and 6.67 hours, depending on how intensively the device is used. Methods to improve this are switching to a power source with a voltage that differs less from the voltage used by the Arduino, because the power regulator of this microcontroller is not very efficient. Another thing I can do is to make use of the power saving sleep mode of the Arduino.

Neglecting the influence of the construction, the material (ABS) of the outer shell of the product is strong enough to survive normal use and an accidental fall on the ground.

Reflection

I found it challenging to apply the things I learned during the course to a real life situation. Unlike the exercises in the book the problems in a project are not directly solvable. I have to define a lot of things myself. Examples are the voltages of the rgb-led, the thickness of the outer shell of the product and the mass of the product. I was able to measure some information myself, or to look it up in the datasheet of a component.
Some things however, are based on assumptions. One example of this is the height at which a young child is holding the device. This height has a big influence on the potential energy and therefore on all calculations that I based on this amount of energy.

What I learnt from this assignment is the great use of physics to create better working and more durable projects. I can for example give an estimation of the battery life and see if a material can survive the forces that are exerted on a product while it is in use. In my next project I will do these kind of calculations in a earlier phase of the project. Another thing I want to improve is to define more information out of actual data rather than assumptions. This will make the research more reliable.

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