Inverted Pendulum v.2.0
User Manual

Document version 1.0.0

Optimal Control Labs
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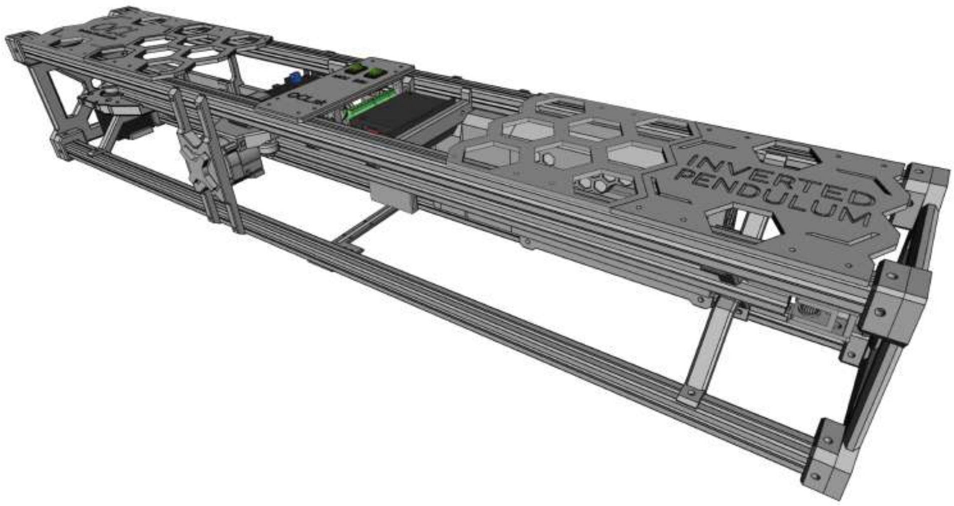
Contents

1 Device Description and Features

1.1 Device Overview



1.2 Dynamical Properties

Inverted Pendulum device is a well-known dynamic process that is very useful in testing of control algorithms. The reason is its fast and nonlinear dynamics. In addition, multiple control scenarios can be tested on it. The device described below was developed to test theoretical results for educational and research purposes. The principle of operation of the inverted pendulum is relatively simple. The pendulum mounted on a cart has two equilibrium states. One is stable and the other is unstable. The point is to move with the cart to control the angle of the pendulum.

The steady-state equilibrium is when the pendulum hangs freely downwards, i.e., its center of gravity is below its axis of rotation. The control scenario, in this case, is as follows: The sequential application of the control actions, i.e., the movement of the cart with the axis of rotation of the pendulum is mounted on. The movement of the cart causes the swinging of the pendulum. The goal is to turn the pendulum $\pi/2$ radians and reach an upper unstable equilibrium position.

In the unstable upper position, the pendulum is prone to fall to the side. The task of the control algorithm is to prevent the pendulum from falling and to stabilize it in the unstable upper position.

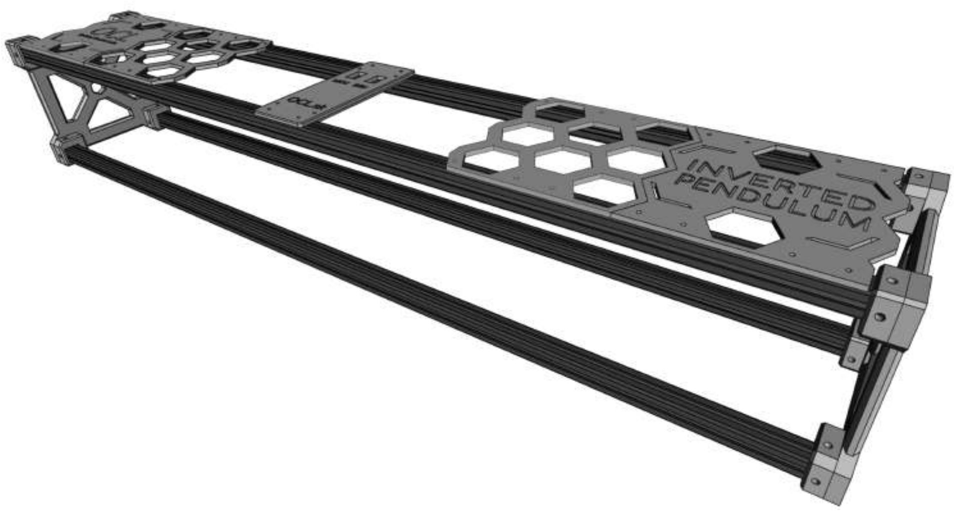
Besides the control of the pendulum's angle, it is also necessary to control its angular velocity, the position of the cart, and the speed of the cart. In addition, all with respect to the system's limitations, such as a limited range of the cart position.

1.3 Specifications Summary

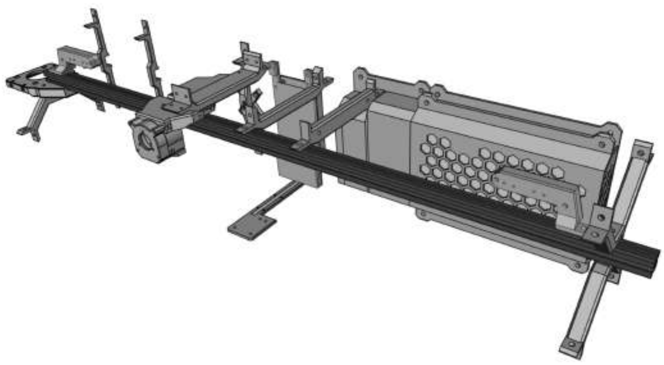
Interface	UART over USB (Serial port 115200/8-N-1)
Electronics Power Supply	+5VDC via USB (Type A to Type B Micro)
Motor Power Supply	+12VDC from built-in power supply
Rotary Encoders	2x SEN0230, 400 pulses per revolution
Motor Driver	TB6600
Stepper Motor	23HS5628-8.00
Power Supply	MEAN WELL RS-150-12
Device Dimensions	length: 1020 mm, widht/height: 172 mm

1.4 Construction Design

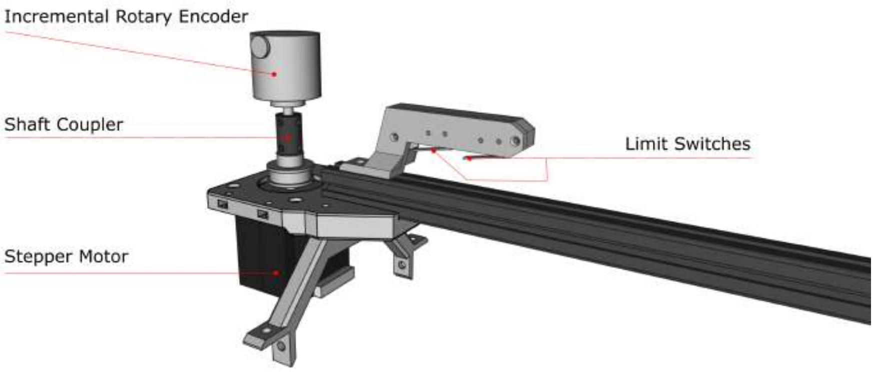
The outer construction of the pendulum consists of extruded aluminum profiles and custom-designed elements made of PET-G material.



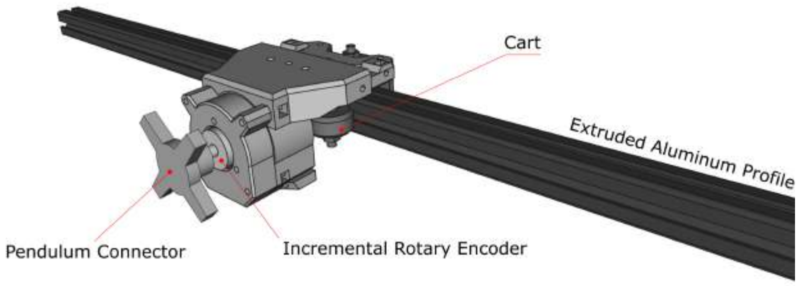
The internal components are also custom-designed and made of either PET-G or PLA +.



There is a stepper motor on the left side of the device and a rotary encoder above it. These two components are coupled by their shafts, so the rotary encoder senses the movement of the motor shaft. Stepper motor has a gear with 40 teeth. Two limit switches prevent the crash of the cart. Limit switch (1) is connected to MCU and its state can be read by microprocessor. Limit switch (2) is connected to ENABLE pin on stepper motor driver. Power supply voltage is disconnected from stepper motor by toggling this switch.

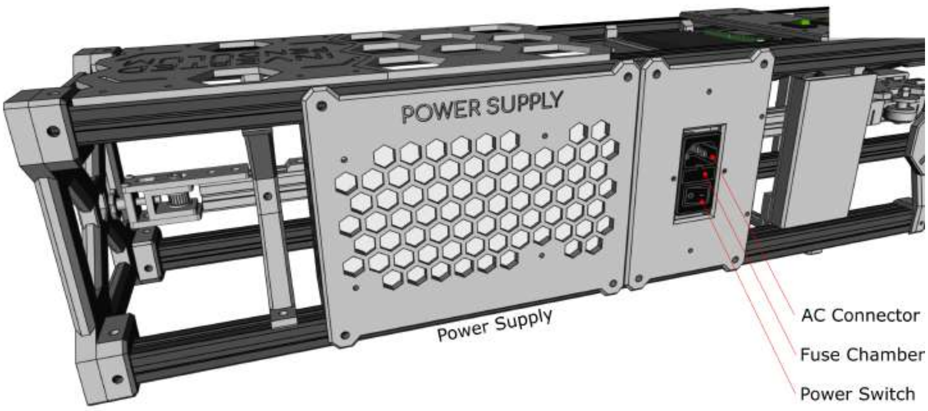


The extruded aluminum profile in the middle of the device serves as a guide for the mobile trolley. There is a platform on the cart that carries the rotary encoder. The connector on the shaft of the rotary encoder is for attaching the pendulum using a nested magnetic mechanism.

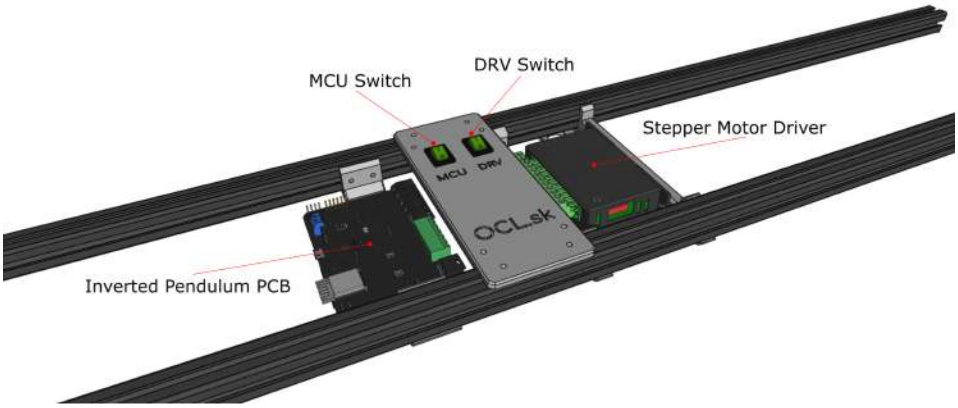


There is a timing belt tensioner on the right side. It serves to tension the timing belt, which transmits the movement from the motor shaft to the cart.

On the backside, there is an AC connector IEC 60320 and a power supply that converts 230VAC to 12VDC.



The electronic platform and motor driver are located on the top of the device.

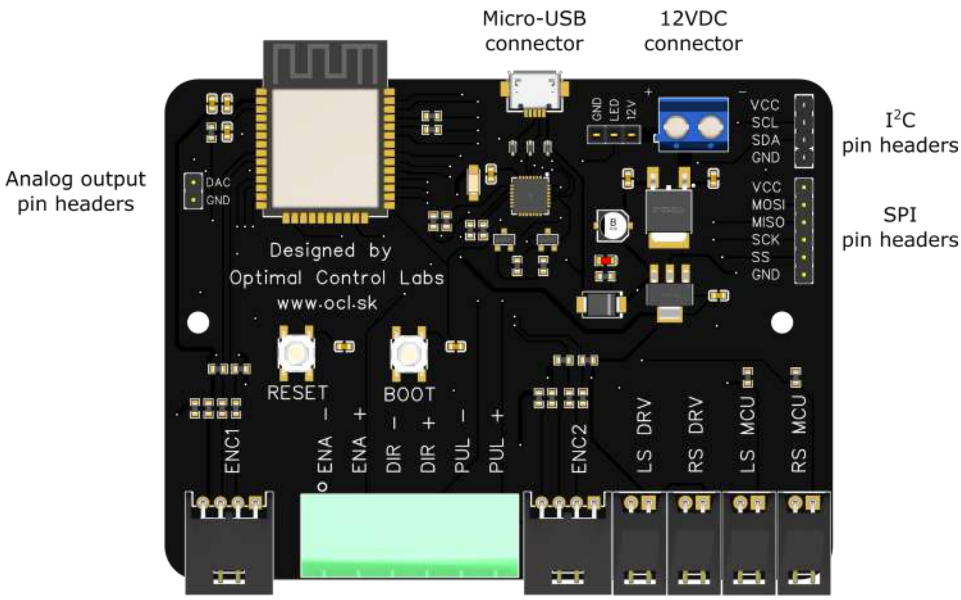


1.5 Recommendations for handling the device

- the device must be placed on the bottom side, such that the side with the electronic platform and the motor driver faces upwards
- when operating the device, it must be placed on the edge of the table, such that the pendulum can swing freely in front of it. Make sure that there is at least 50 cm of adequate space around the device
- the device is safe to carry by its sides. When you need to move the device, hold it by its side parts.

1.6 Electronic Platform

The inverted pendulum device contains its own custom-designed electronic platform. The is equipped with the ESP32 microprocessor, whose parameters are listed in the table 1.



Name	ESP32-WROOM-32D-N16
Core	Xtensa®32-bit LX6 dual-core processor
ROM	448 kB
SRAM	520 kB
FLASH	16 MB
Crystal Oscillator	40 MHz

Table 1: The list of ESP32 parameters.

The electronic board also contains a set of connectors for connecting components such as rotary encoders, switches, motor driver, etc. The description of functions of individual connectors is given in table 2. There is also a pair of connectors on the PCB for connecting devices - such as sensors or displays that communicate using the I^2C or SPI protocols. Pin DAC can be used either as an input or output. In case of the output, the digital-to-analog converter is available.

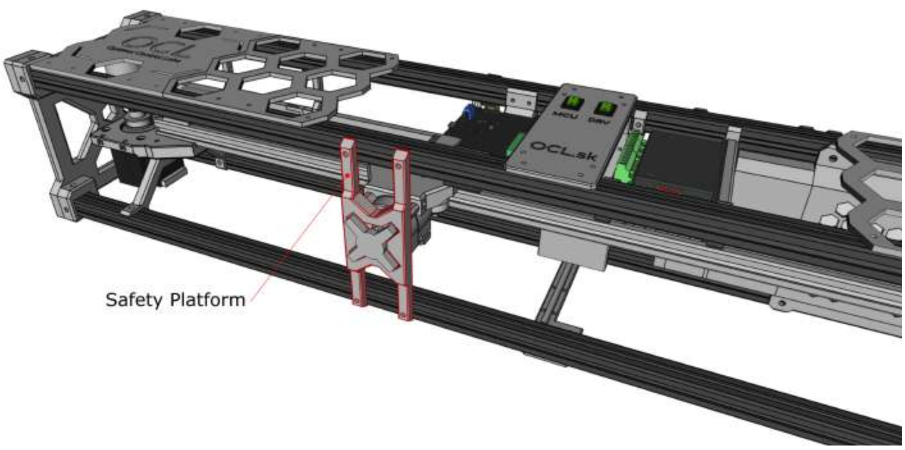
PCB Mark	Description	MCU GPIO
ENC1	Pendulum rotary encoder	32, 33
ENC2	Motor rotary encoder	26, 27
LS DRV	Left switch connected to motor driver	NC
RS DRV	Right switch connected to motor driver	NC
LS MCU	Left switch connected to microprocessor	14
RS MCU	Right switch connected to microprocessor	15
ENA	Enable signal for motor driver	4
DIR	Direction signal for motor driver	16
PUL	Pulse signal for motor driver	17
DAC	Analog output	25
LED	Allows to connect programmable LED strip	13

Table 2: PCB connectors descriptions.

2 Getting Started

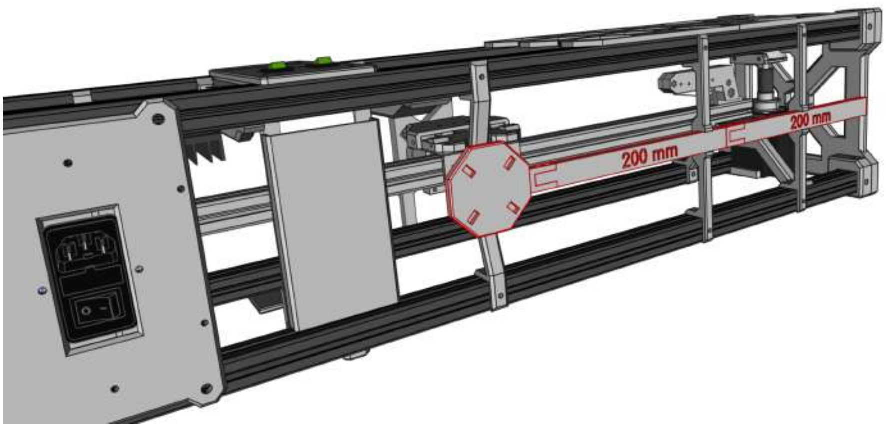
2.1 Assembly

1. Remove the safety platform.

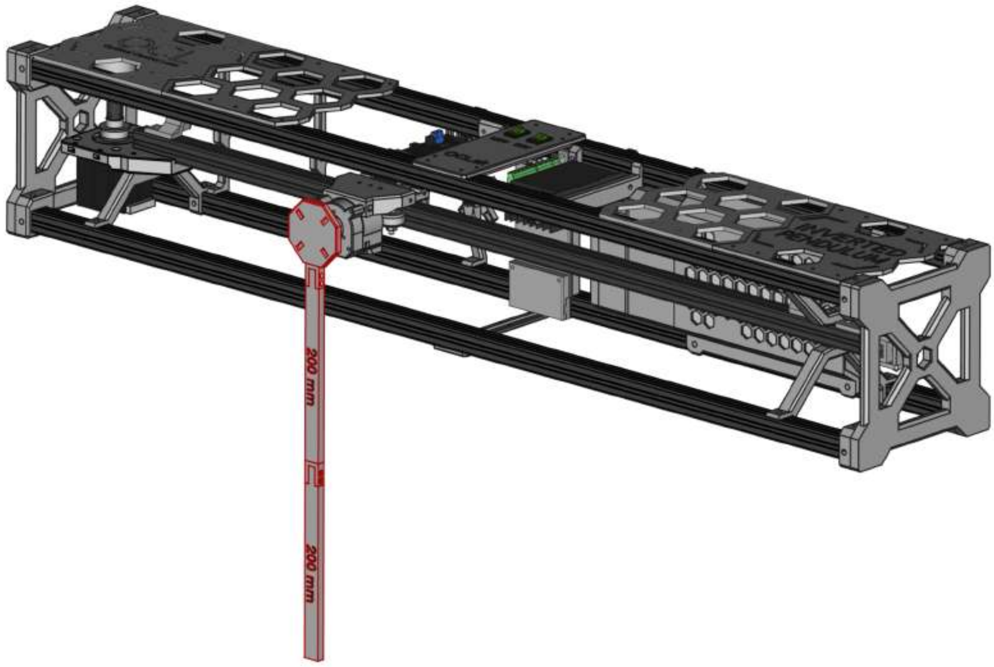


***Notice**: The rotary encoder shaft can be easily damaged by bumps. Therefore, to keep the encoder safe, always use the safety platform during shipping or handling the device.*

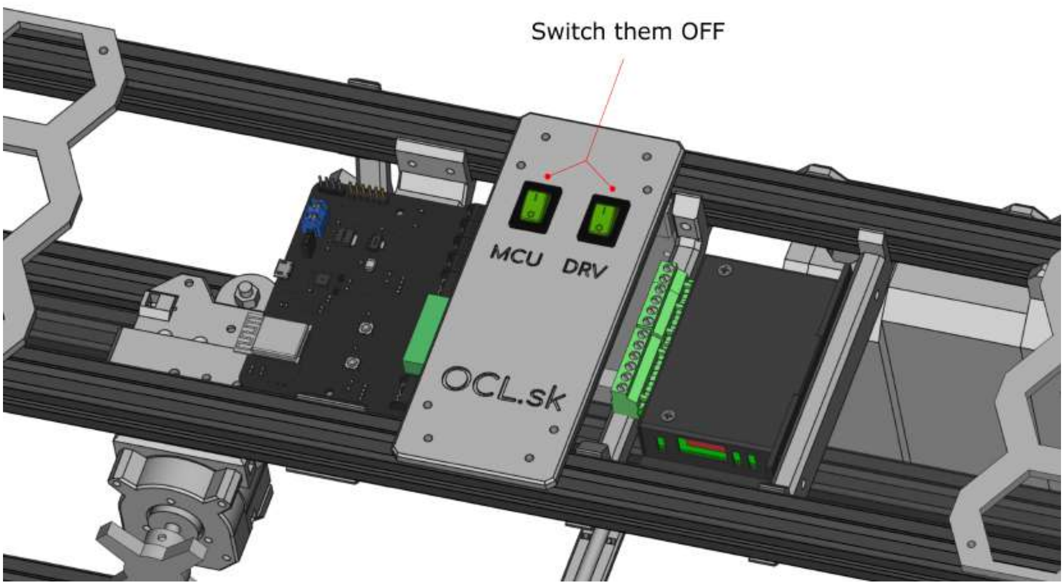
2. Unplug the pendulum from the backside of the device. It is mounted on a magnetic connector. You can unplug it by using a reasonable amount of force.



3. Plug it onto the magnetic connector on the rotary encoder and wait until it stops swinging. It should fit exactly into the grooves and should not move freely forwards and backwards.



4. Switch OFF the MCU and DRV power supply switches.



5. Plug the EURO power cable into the AC connector on the backside.

Now, the device is properly prepared to its operation. Do not disassemble or modify the device in any way. Improper handling of the device can damage it.

2.2 Run a Showcase

It is not necessary to program or connect the device to the computer to start the device and demonstrate pendulum stabilization. The device has a pre-programmed pendulum stabilization algorithm using an LQR controller. To start and run the basic controller, follow the instructions:

1. Follow all the instruction for assembling and preparing device from section 2.1.
2. Switch ON the AC connector on the backside of the device.
3. Switch ON the MCU, and DRV green switches.
4. Press the RESET button on the PCB.
5. Carefully rotate CW (a clockwise direction) the pendulum into its upright position by your hand. The LQR algorithm takes over after the pendulum crosses the upright vertical position.

In case the inverted pendulum falls to the side or hits the limit switches:

1. Switch the MCU, and DRV switches OFF immediately.
2. Move the cart into the middle position with your hand.
3. Repeat the previous procedure.

You can freely tune and edit the pre-programmed controller. The script with the controller is located at GitHub

2.3 Connection to PC and Installation

The operating system of computer that device is connected to must have installed an USB-to-serial driver for the device to function properly. Use Micro USB cable to connect the Inverted Pendulum to the USB Type A port on a host computer.

The most popular environment to code the ESP32 micro-controller is *Arduino IDE*, but feel free to choose any other IDE. A detailed guide on how to install Arduino IDE is here. The software is for free.

To be able to program boards with an ESP32 microprocessor, you need to follow the instructions here.

Both manuals contain installation procedures across multiple operating systems.

2.4 Important Constants and Calculations

The implementation of a controller either for stabilization of the pendulum in its upright vertical position or any other control scenario directly into the micro-controller requires proper measurements and control actions.

2.4.1 Sensing a pendulum's angle

The angle of the pendulum is measured by Incremental Rotary Encoder (ENC1 connector) assigned to GPIO pins 32 and 33. The encoder generates 400 pulses per revolution per channel. It has two channels, therefore, if the rising and falling edges are encountered, the resulting resolution is 1600 pulses per revolution. If we want to convert the pulses to angle in radians the simple math can be incorporated.

$$deg = \frac{pulses\ 2\pi}{1600}\ [\text{rad}]$$

When the program instance to count the pulses are created, you have to assign the GPIO pins to it. The order 32, and 33 corresponds to counting additive pulses in the CW pendulum's move and subtracting pulses in CCW. If you switch the order of GPIOs, the incrementing/decrementing of pulses will be switched too.

2.4.2 Sensing a cart's position

The position of the cart is measured by the same incremental rotary encoder as in the pendulum's case. The GPIO pins 26, and 27 are assigned to ENC2 connector. Conversion of pulses to position of the cart in milimeters is as follows

$$position = \frac{pulses}{20} \text{ [mm]}$$

2.4.3 Invoking the motor's movement

The device is equipped with stepper motor to invoke the cart movement. Stepper motor requires two kind of signals: Direction and Pulse. Using the third signal ENABLE is optional.

Specially adapted green connector with all three signals is located on PCB. The GPIO 4 is allocated for ENABLE signal. If this signal is pulled HIGH, the stepper motor stops its operation. The GPIO 16 is allocated for DIR signal. When it is HIGH, the cart is moving to the right-hand side. The GPIO 17 is for PUL signal. Each step of the stepper motor is invoked by the rising edge of each pulse generated by this GPIO. The velocity of the cart is directly proportional to the frequency of generated pulses. The controller of the process generates desired acceleration or the velocity of the cart. This value needs to be converted to frequency of generated pulses. The conversion of the velocity to the frequency is as follows:

$$freq = vel * 40$$

where *vel* is desired velocity of the cart.