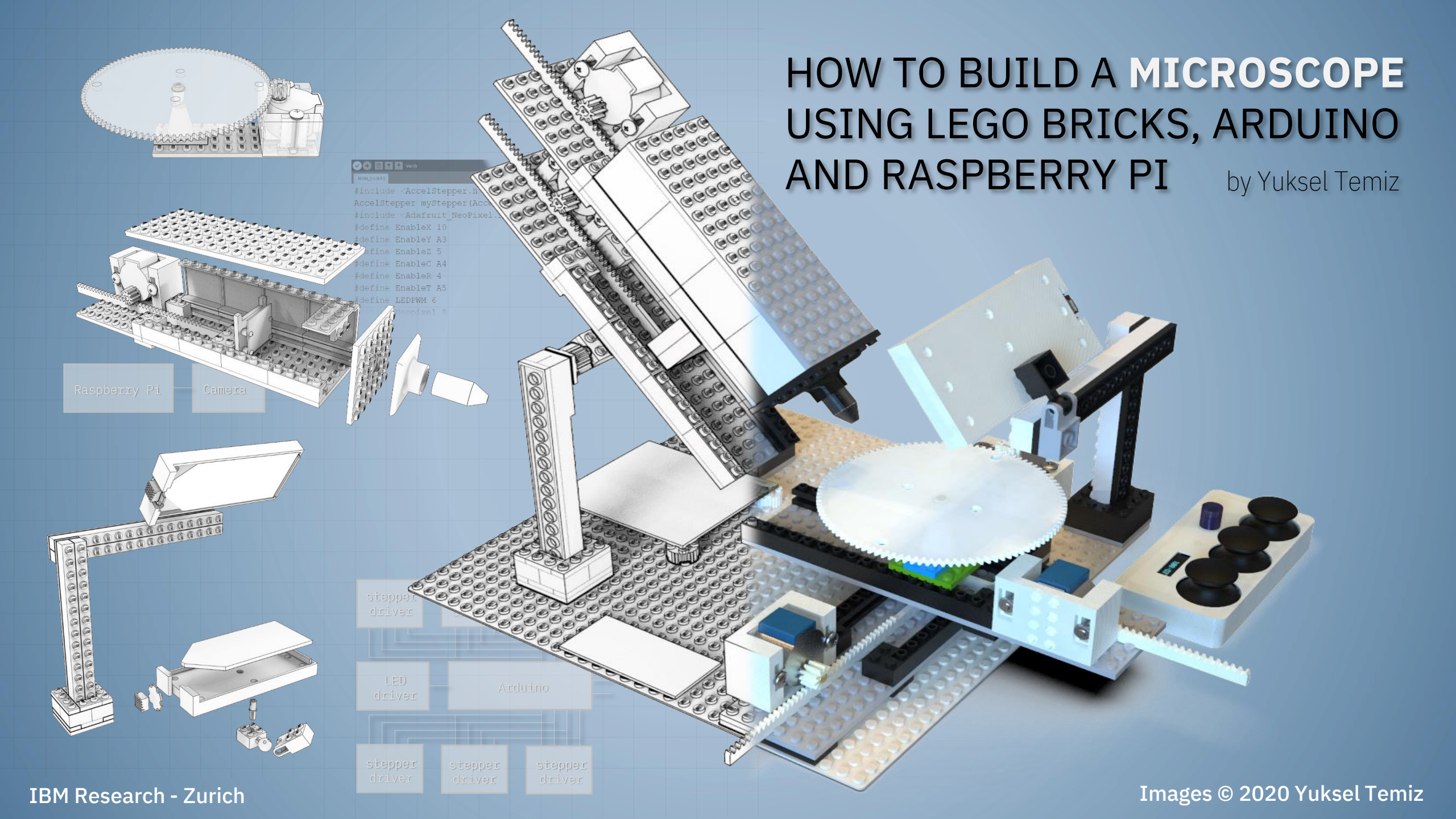
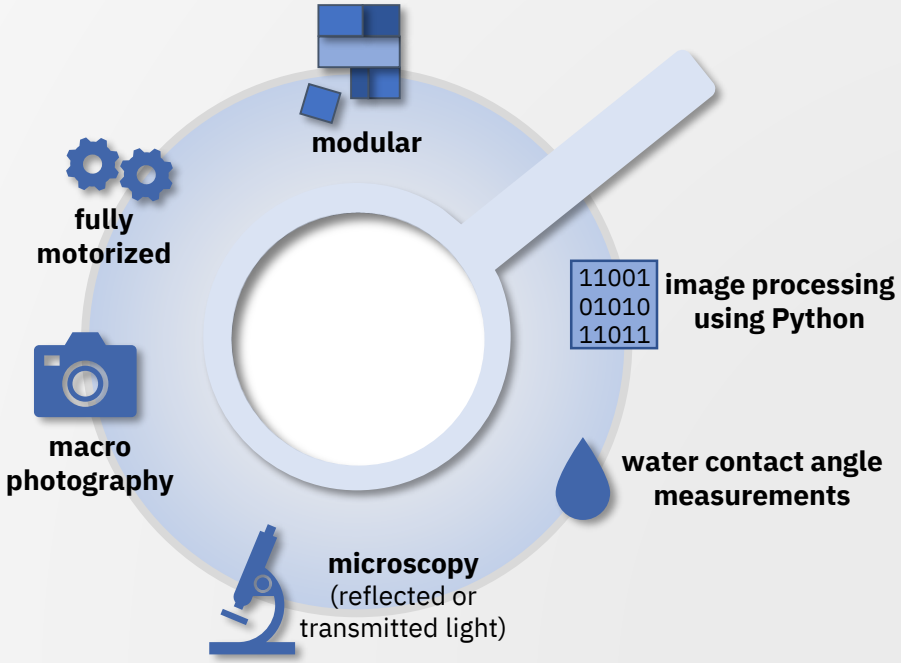
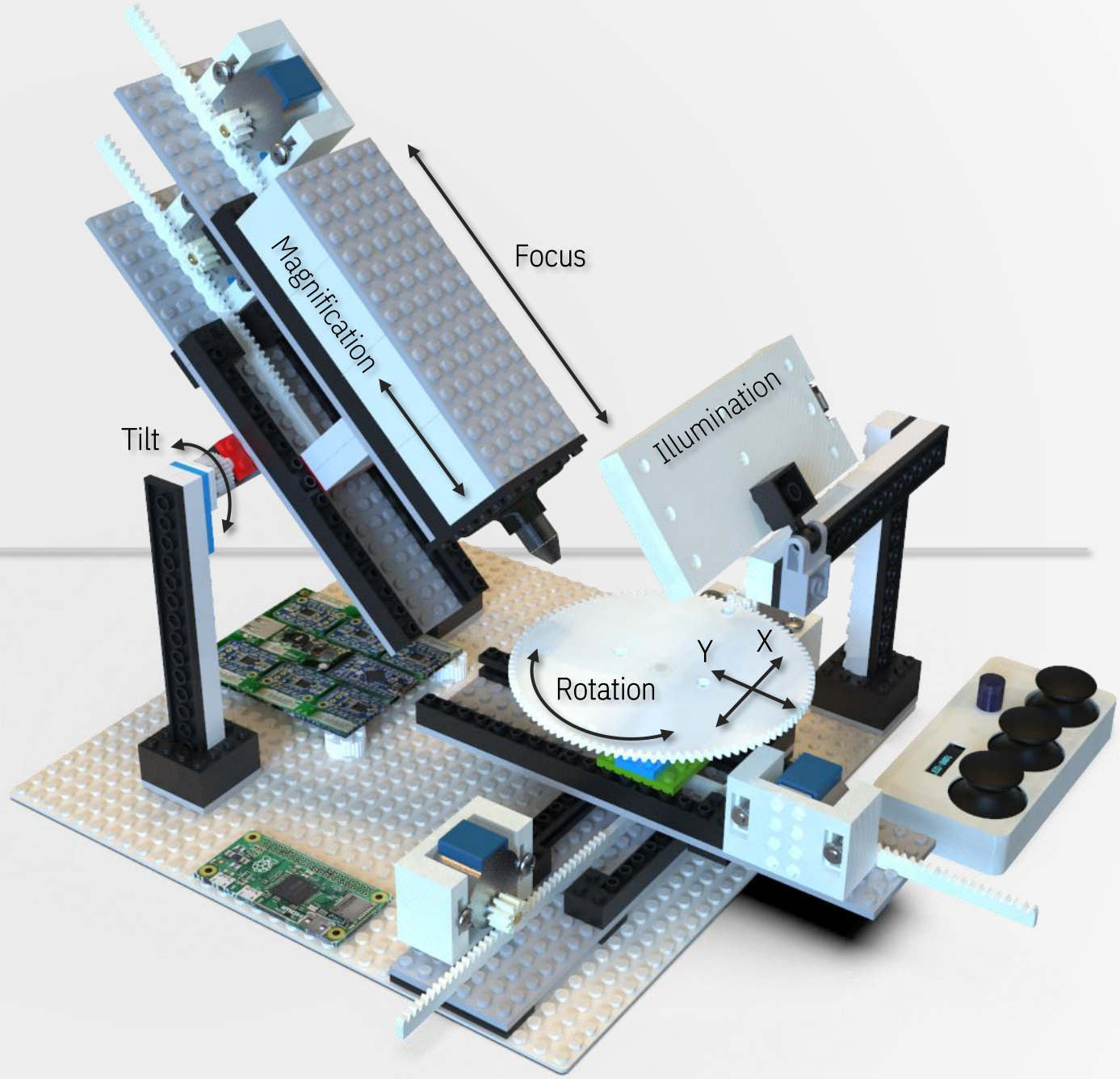

HOW TO BUILD A MICROSCOPE USING LEGO BRICKS, ARDUINO AND RASPBERRY PI
by Yuksel Temiz
Raspberry Pi
Camera
stepper driver
LED driver
Arduino
stepper driver
stepper driver
stepper driver
IBM Research - Zurich
Images © 2020 Yuksel Temiz

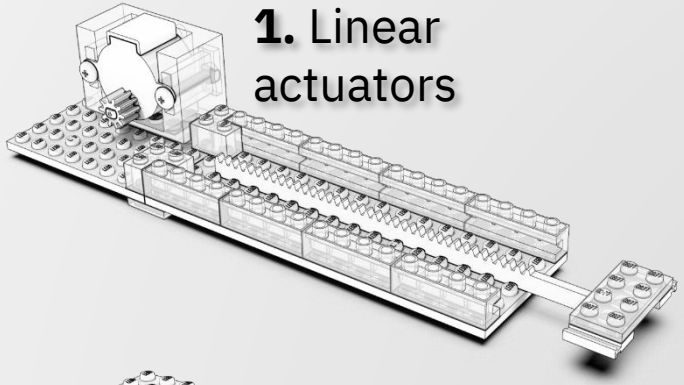




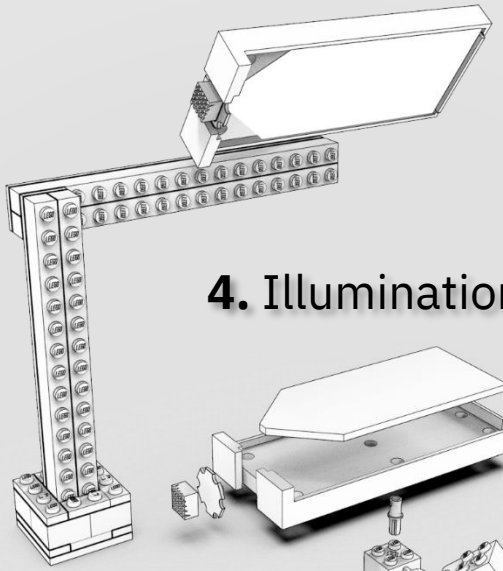
KEY FEATURES

- Raspberry Pi operation system
- 8 MegaPixel CMOS camera (Full HD 30 fps video)
- Imaging features from several centimeters to several micrometers without changing the lens
- 6 stepper motors (X, Y, tilt, rotation, magnification, and focus)
- Variable speed control using a joystick controller or a keyboard
- Uniform illumination for imaging reflective surfaces
- Modular design: stages and modules can be arranged in any configuration depending on the application

Contents

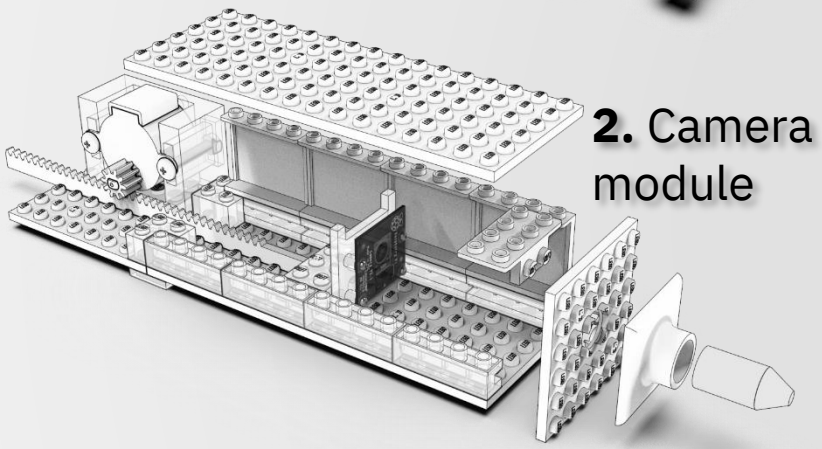


1. Linear actuators

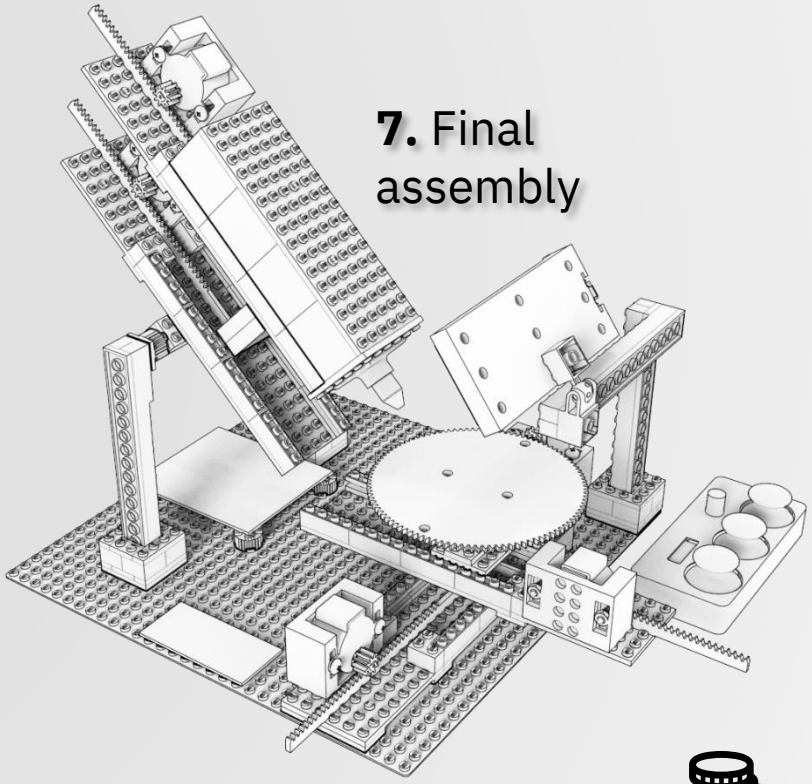


4. Illumination

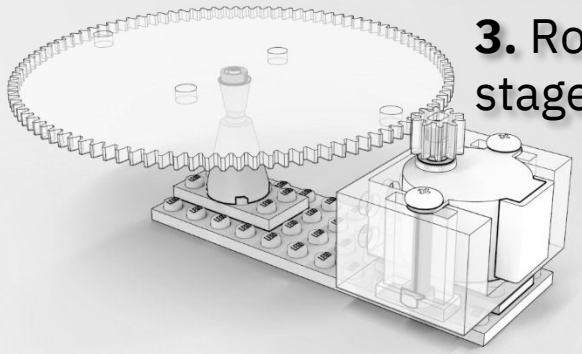
6. Electronics



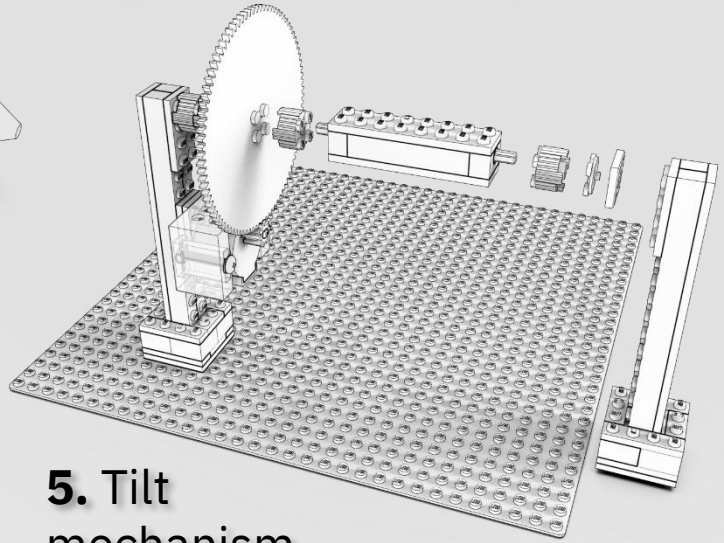
2. Camera module



7. Final assembly

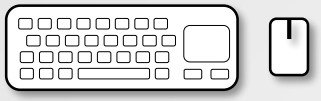


3. Rotary stage



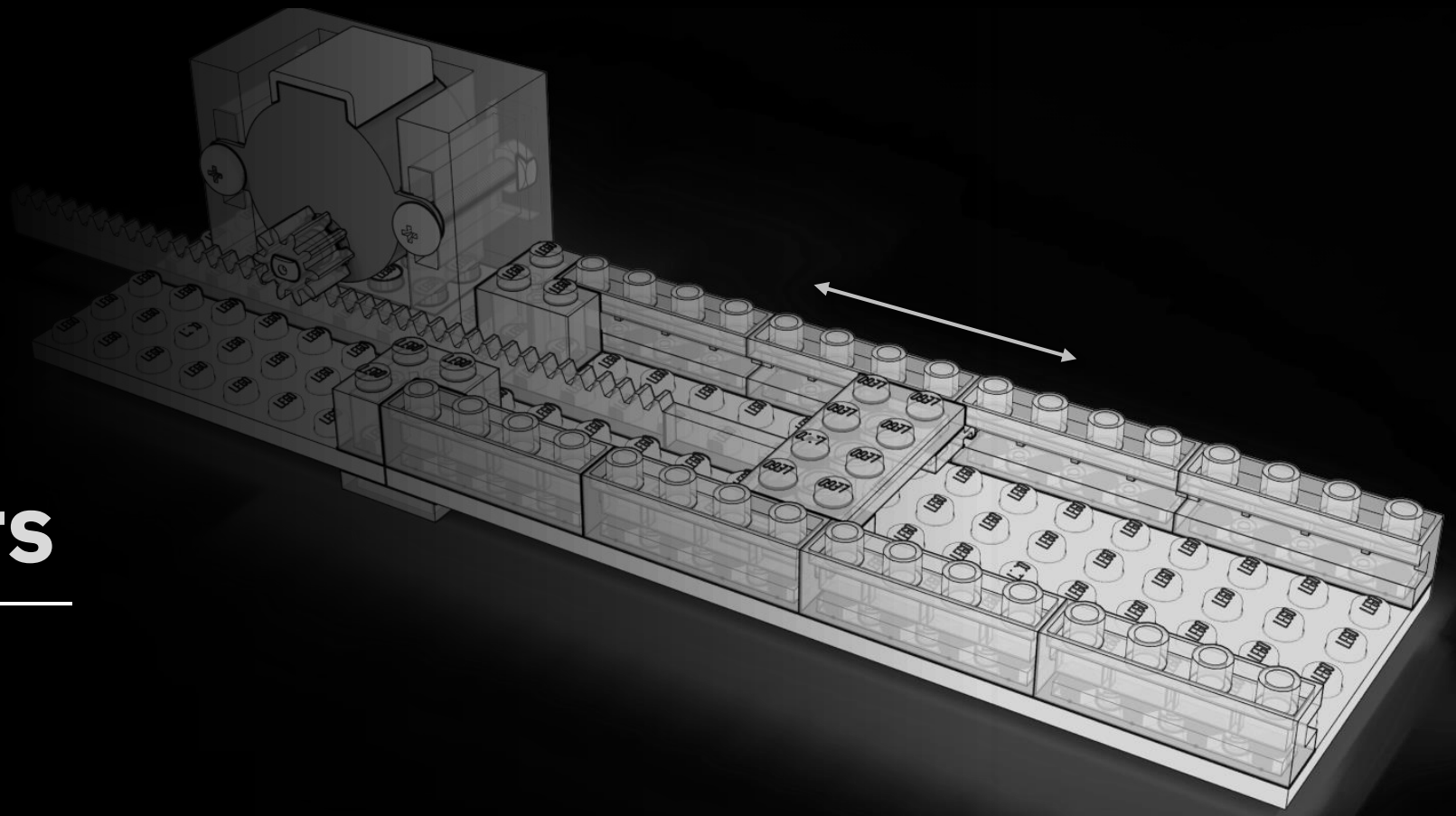
5. Tilt mechanism

8. Software



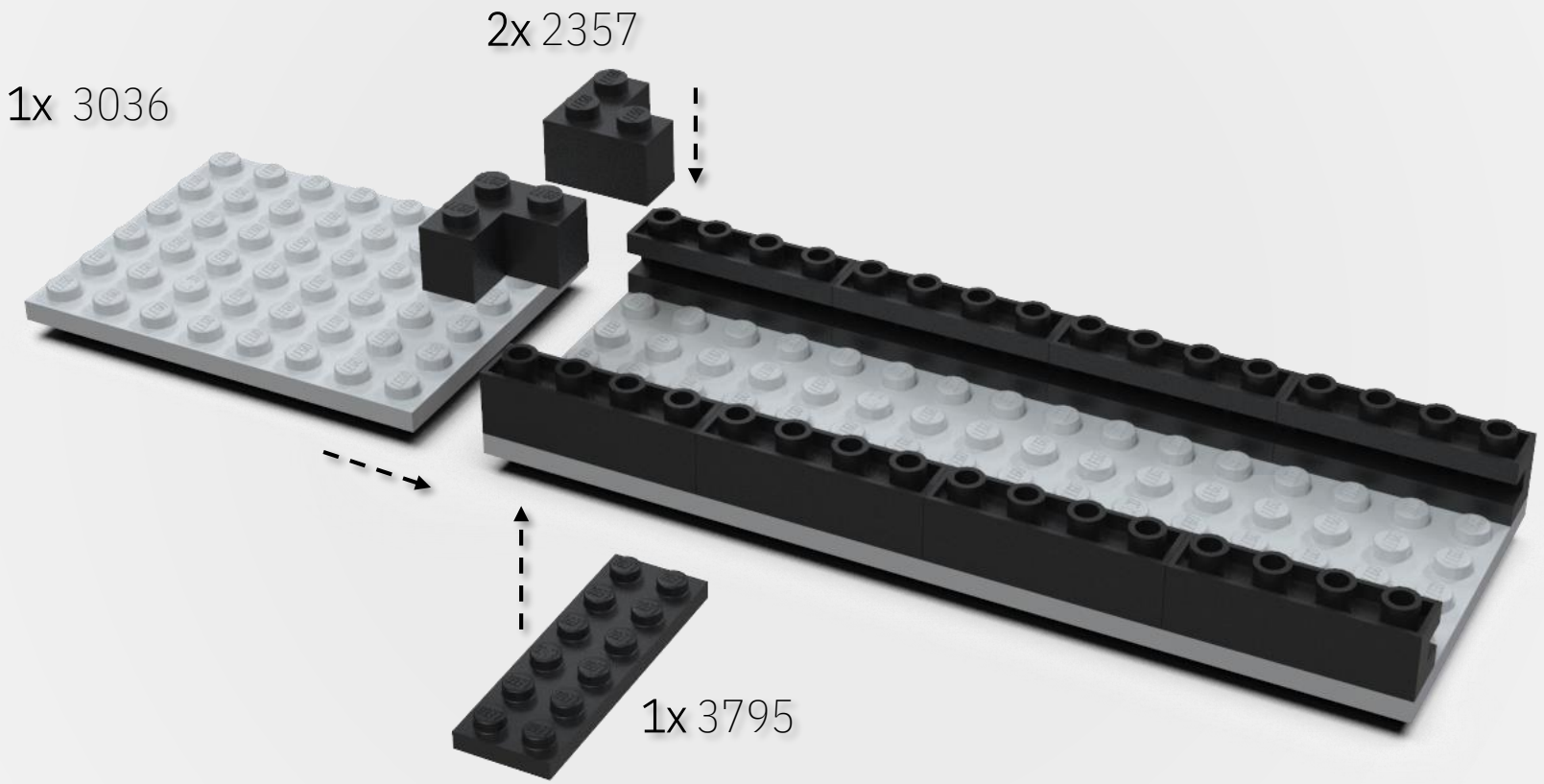
BOM

Linear actuators

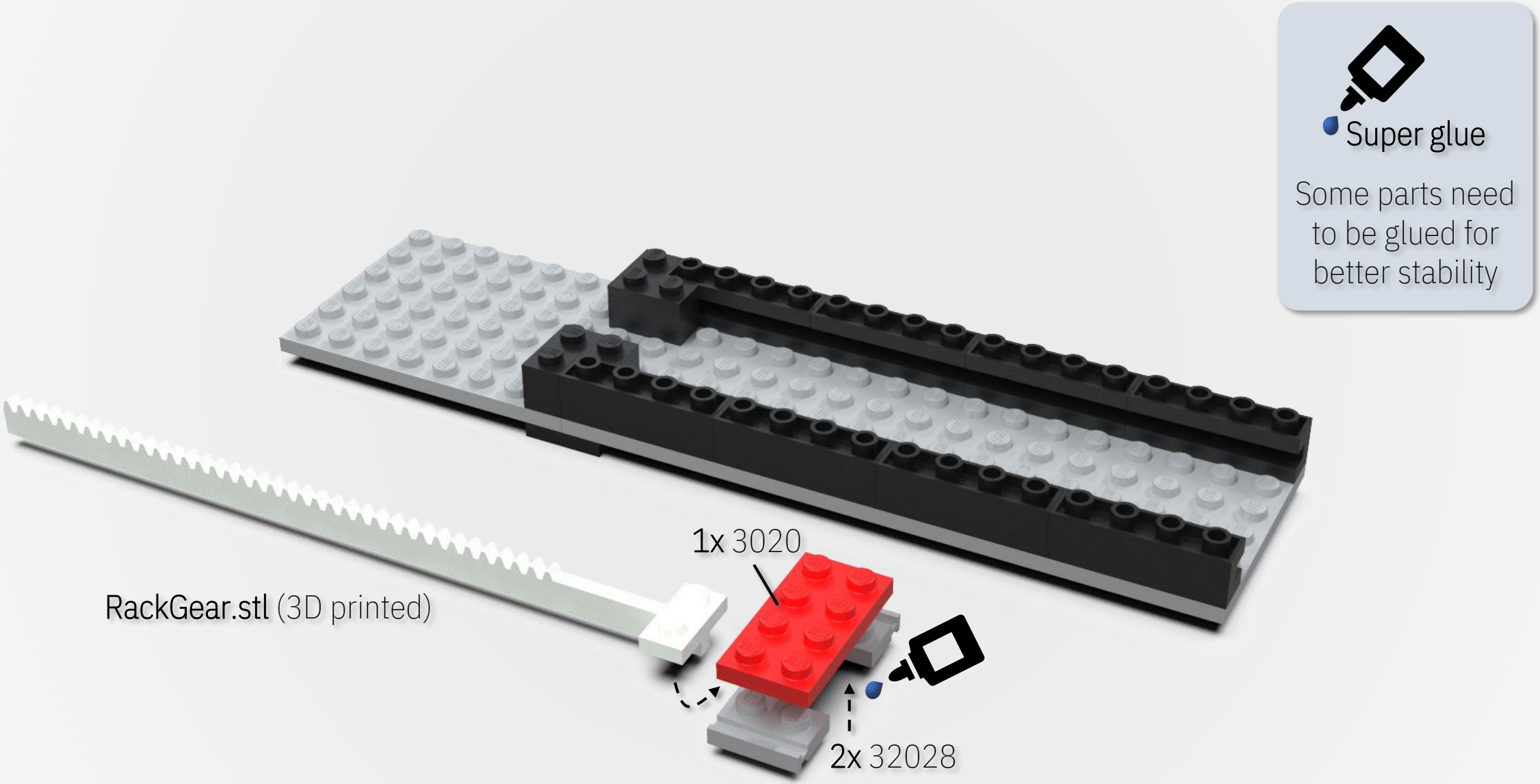


Linear actuators

Linear actuators



Linear actuators



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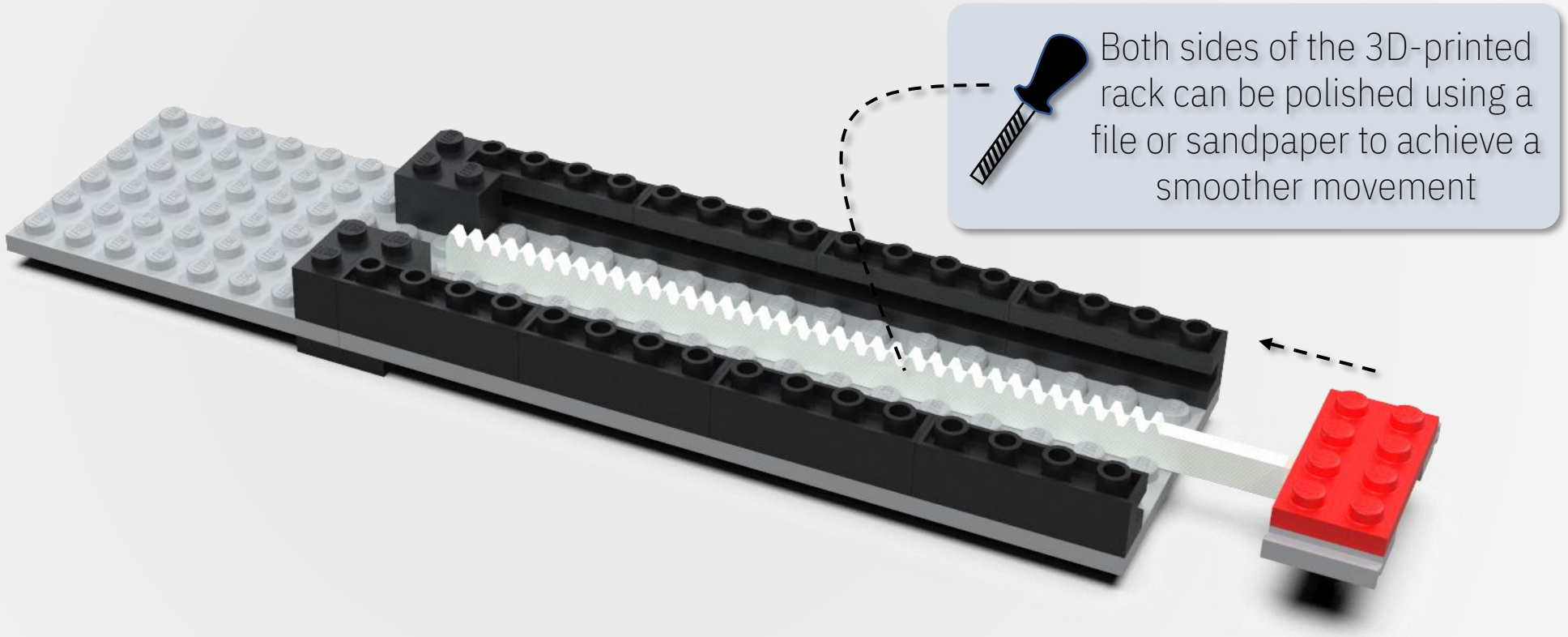

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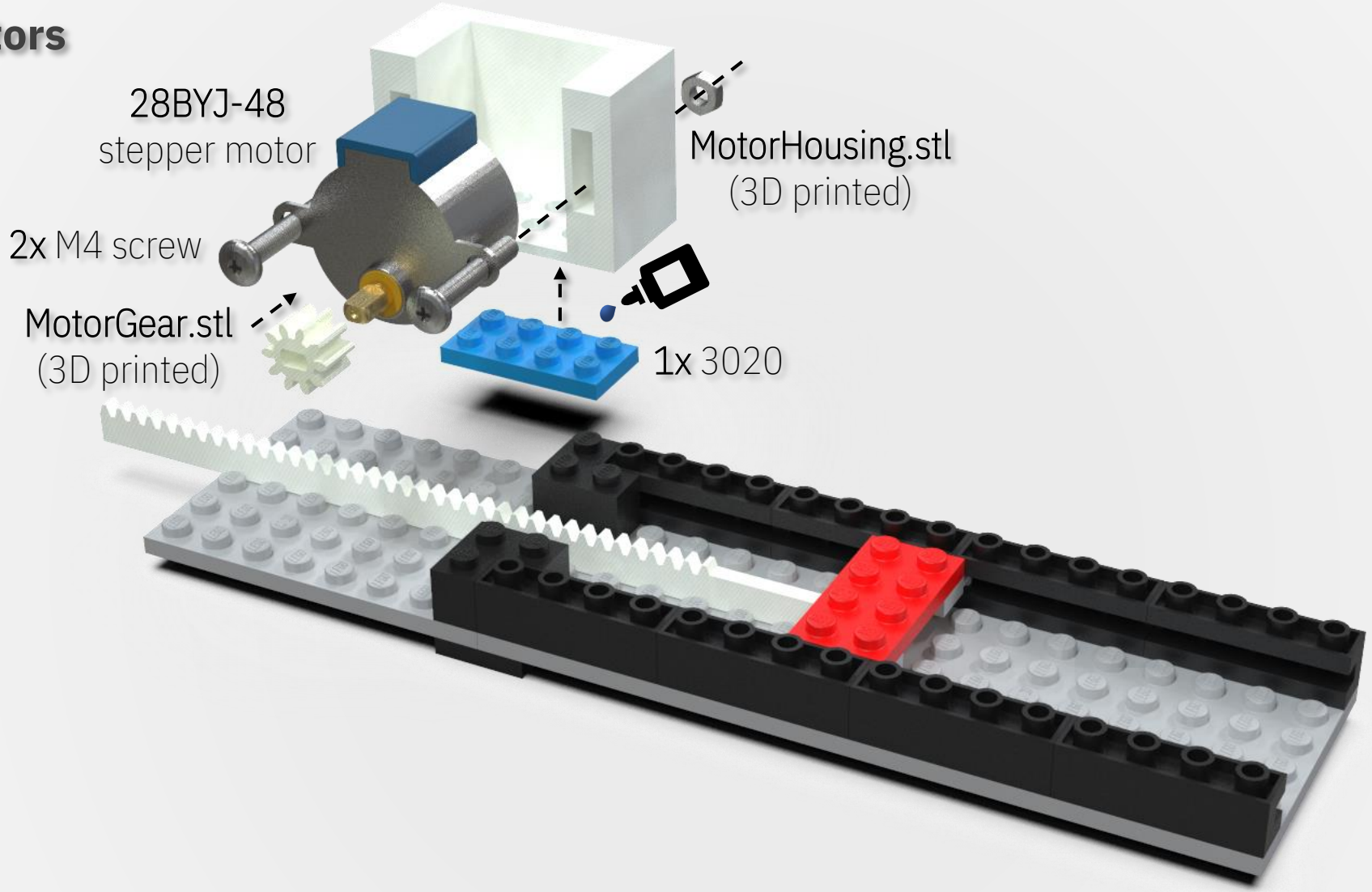
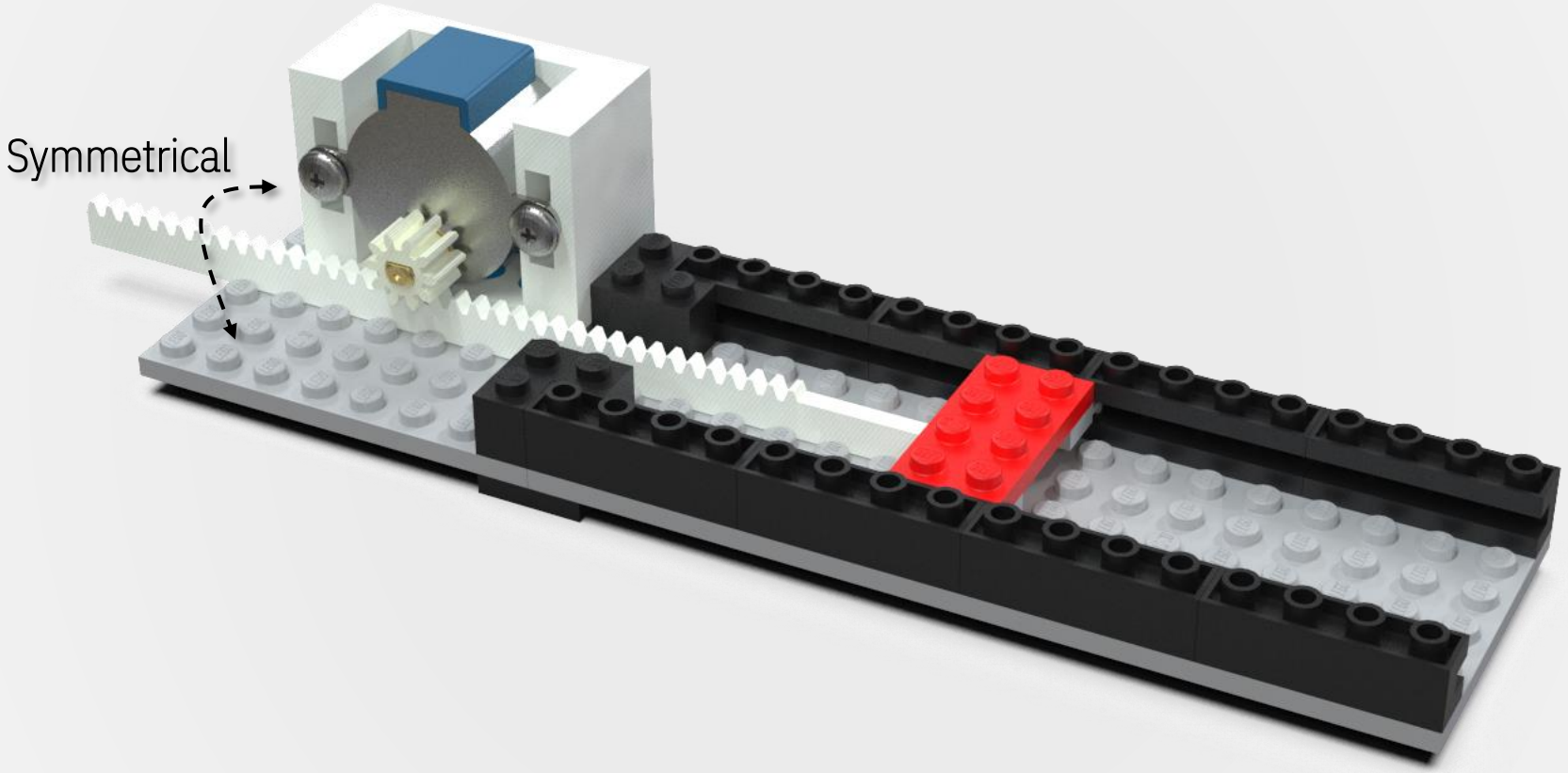


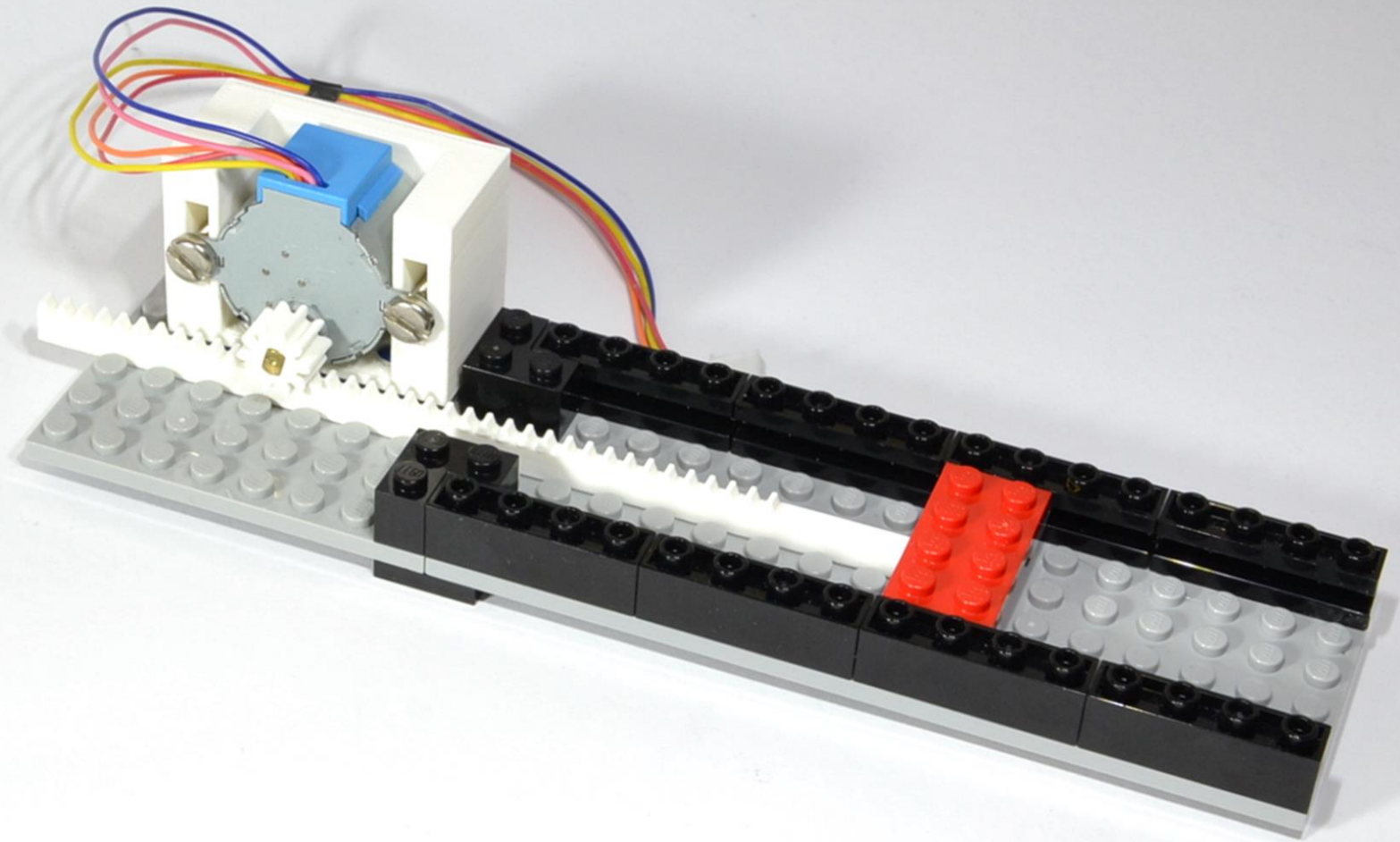
Linear actuators



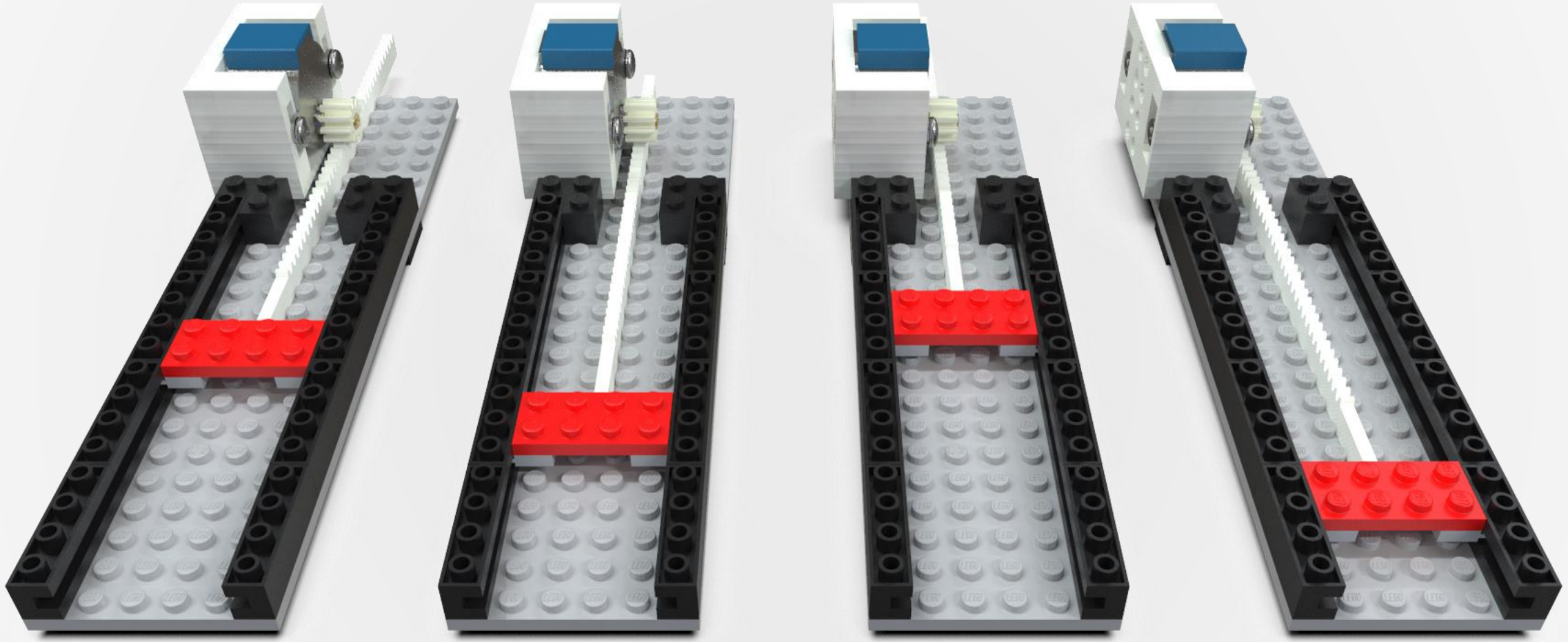
The motor can be positioned on either side of the rack. This would be useful to quickly change the movement direction of the stages with respect to the joystick action (the direction can also be changed from the software).

Linear actuators

(Photograph)



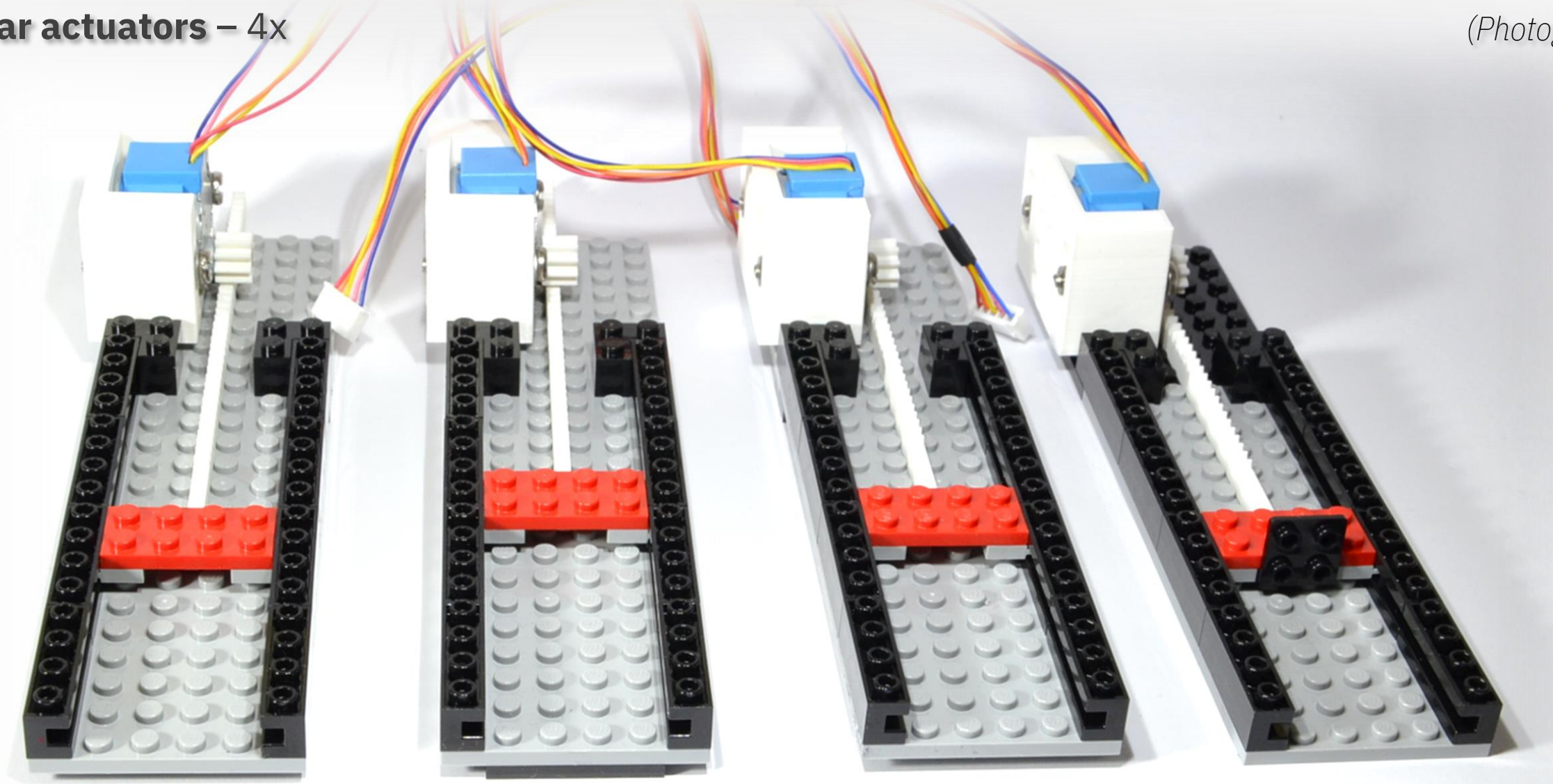
Linear actuators – 4x



X **Y** **Z** **Camera**

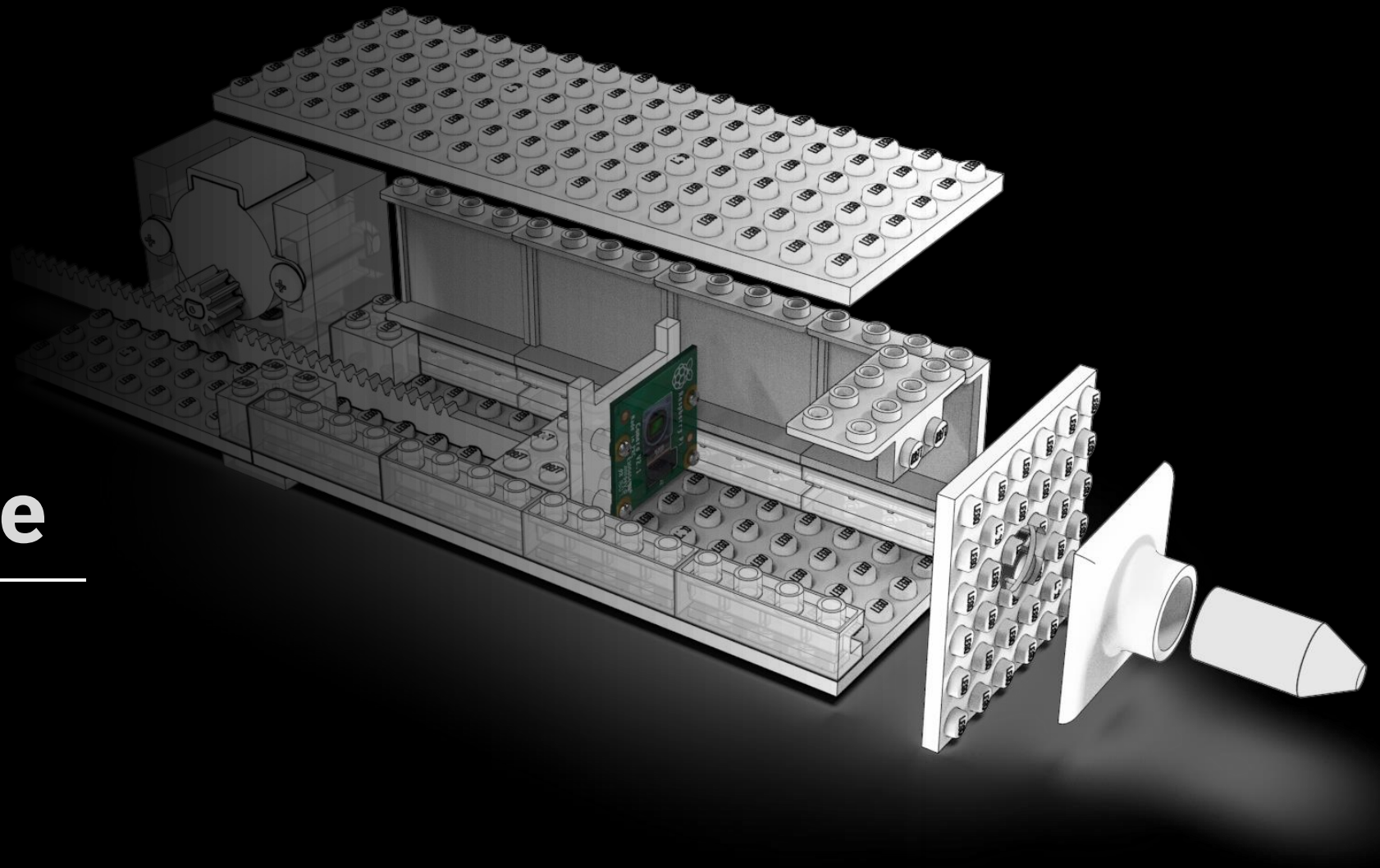
Linear actuators – 4x

(Photograph)



X **Y** **Z** **Camera**

Camera module



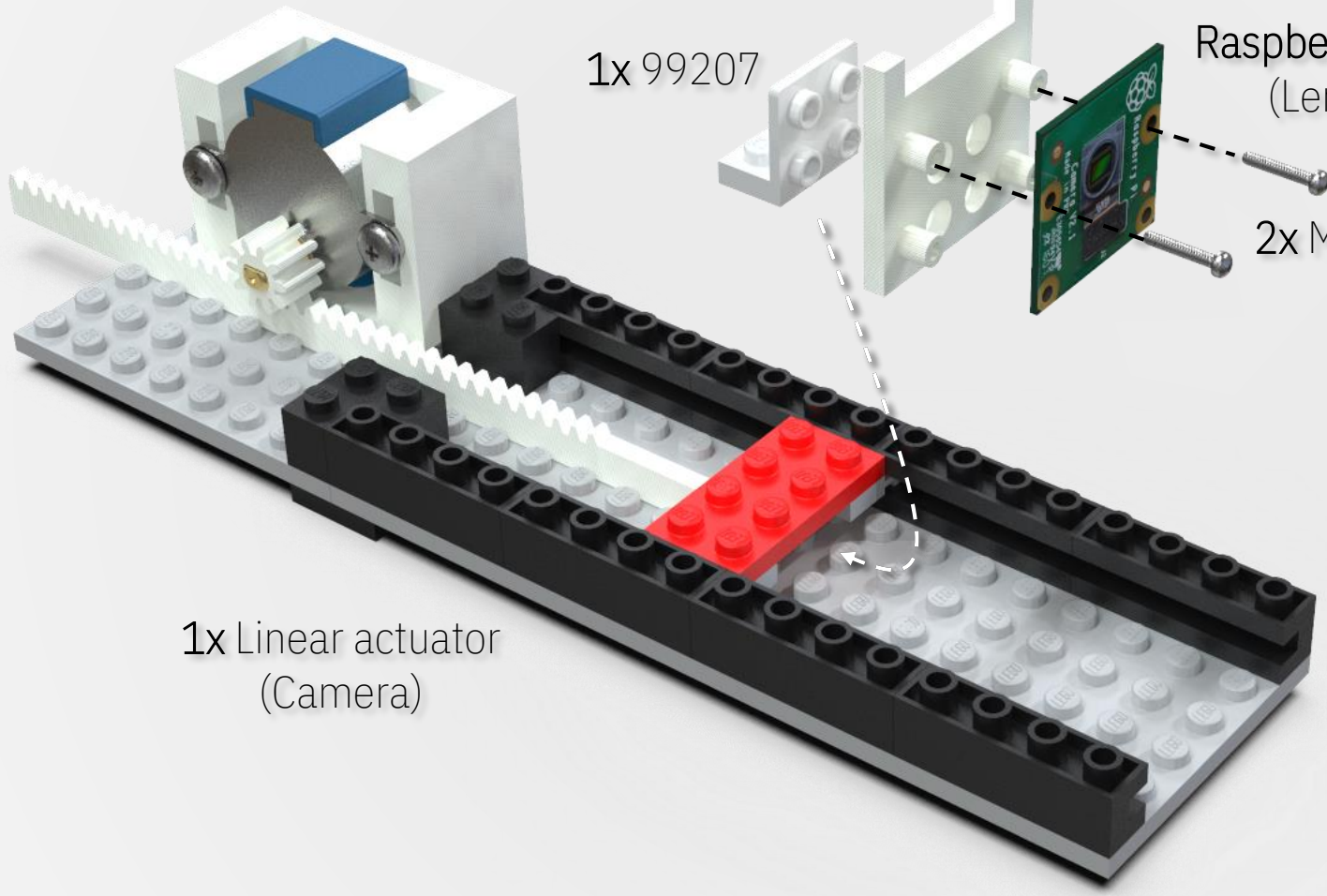
Camera module

CameraAdapter.stl
(3D printed)

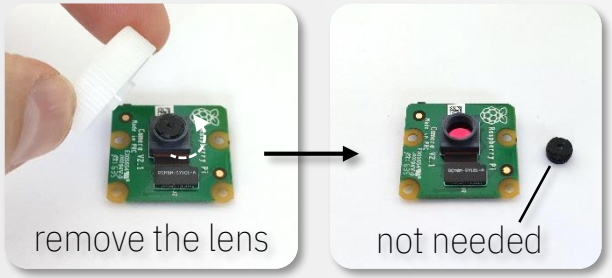
1x 99207

Raspberry Pi camera v2
(Lens removed)

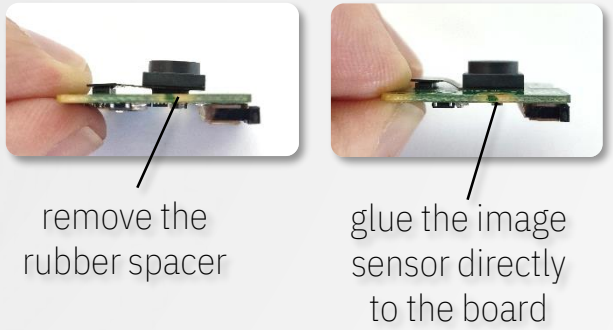
2x M2



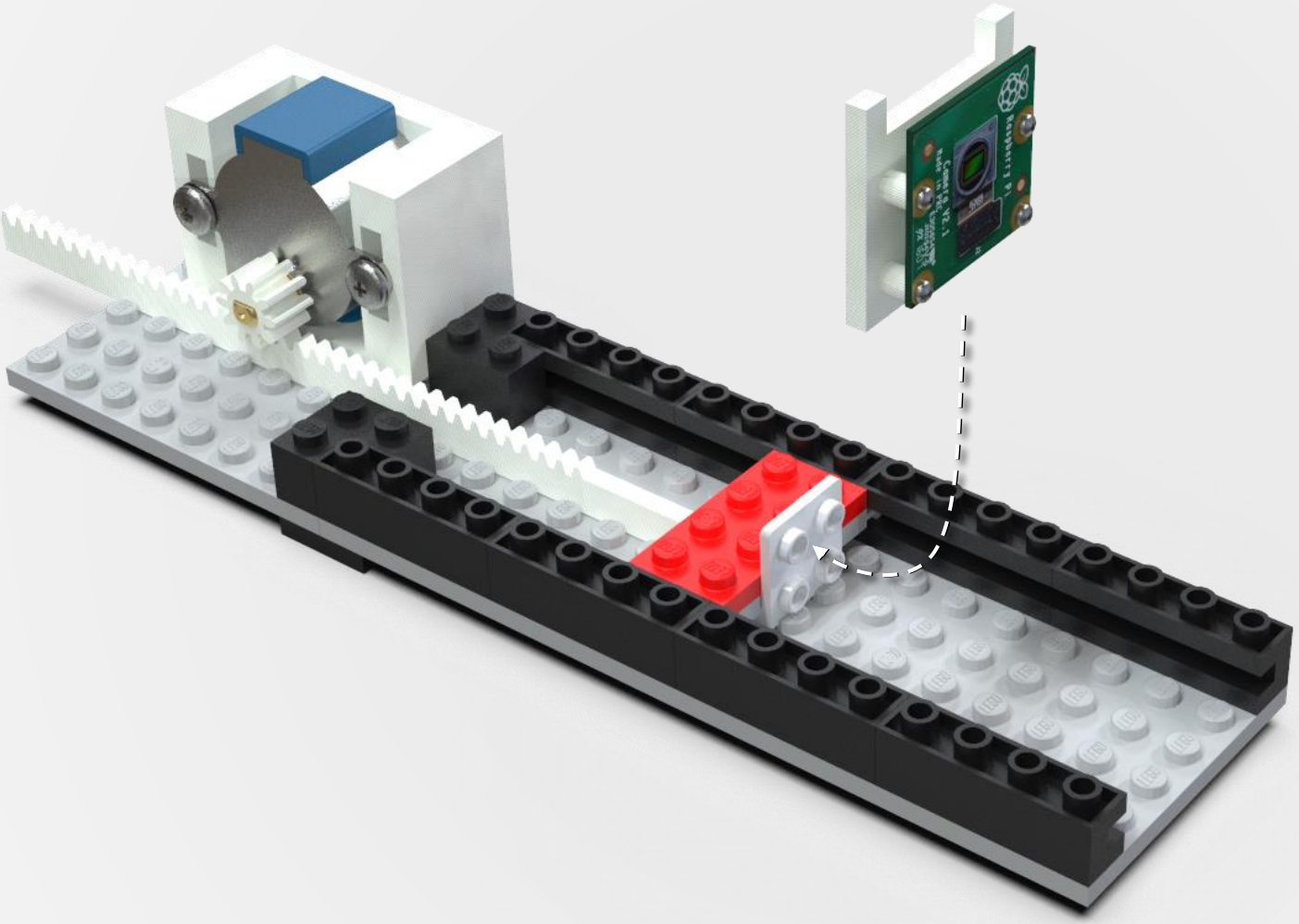
1x Linear actuator
(Camera)



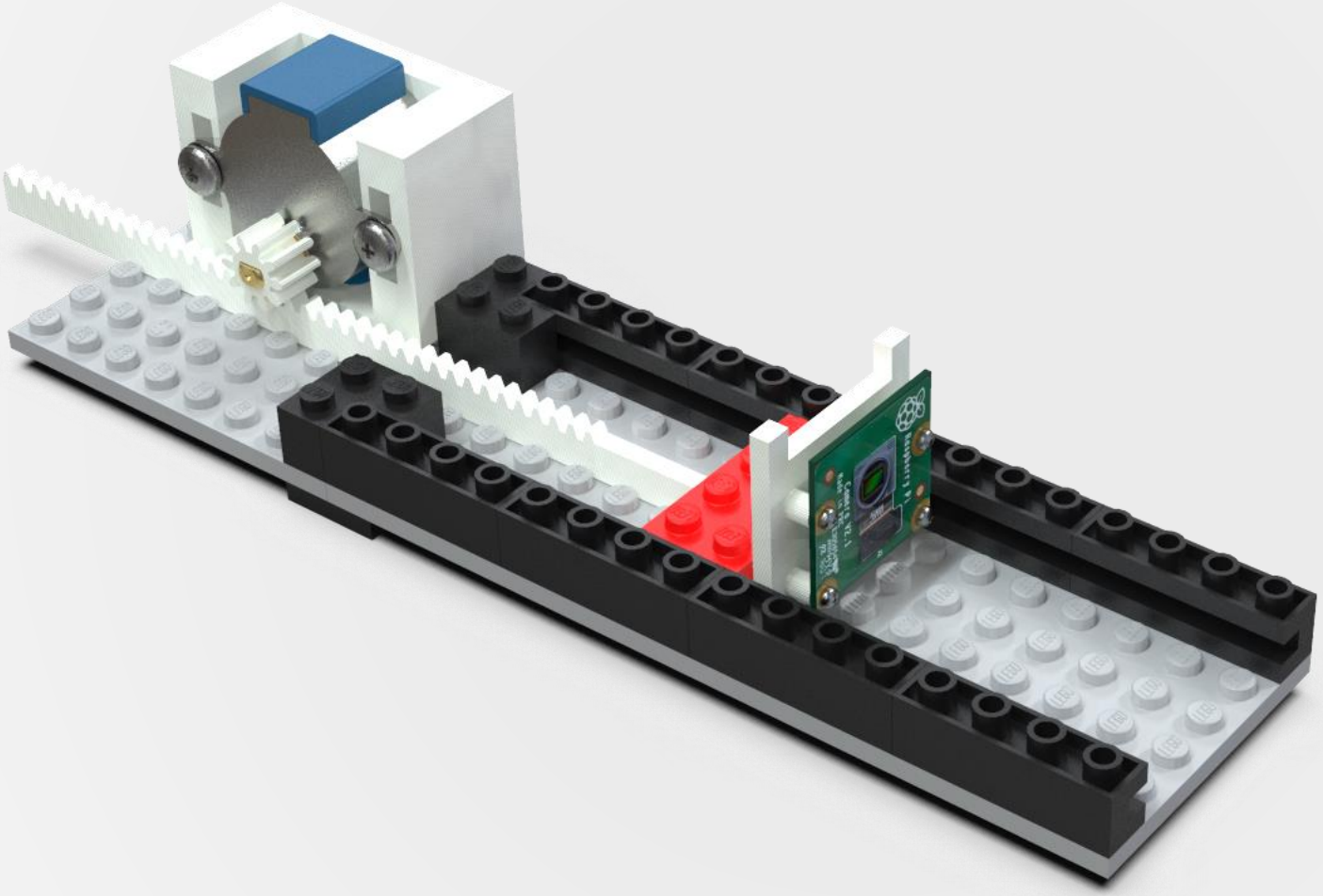
Recommendation:



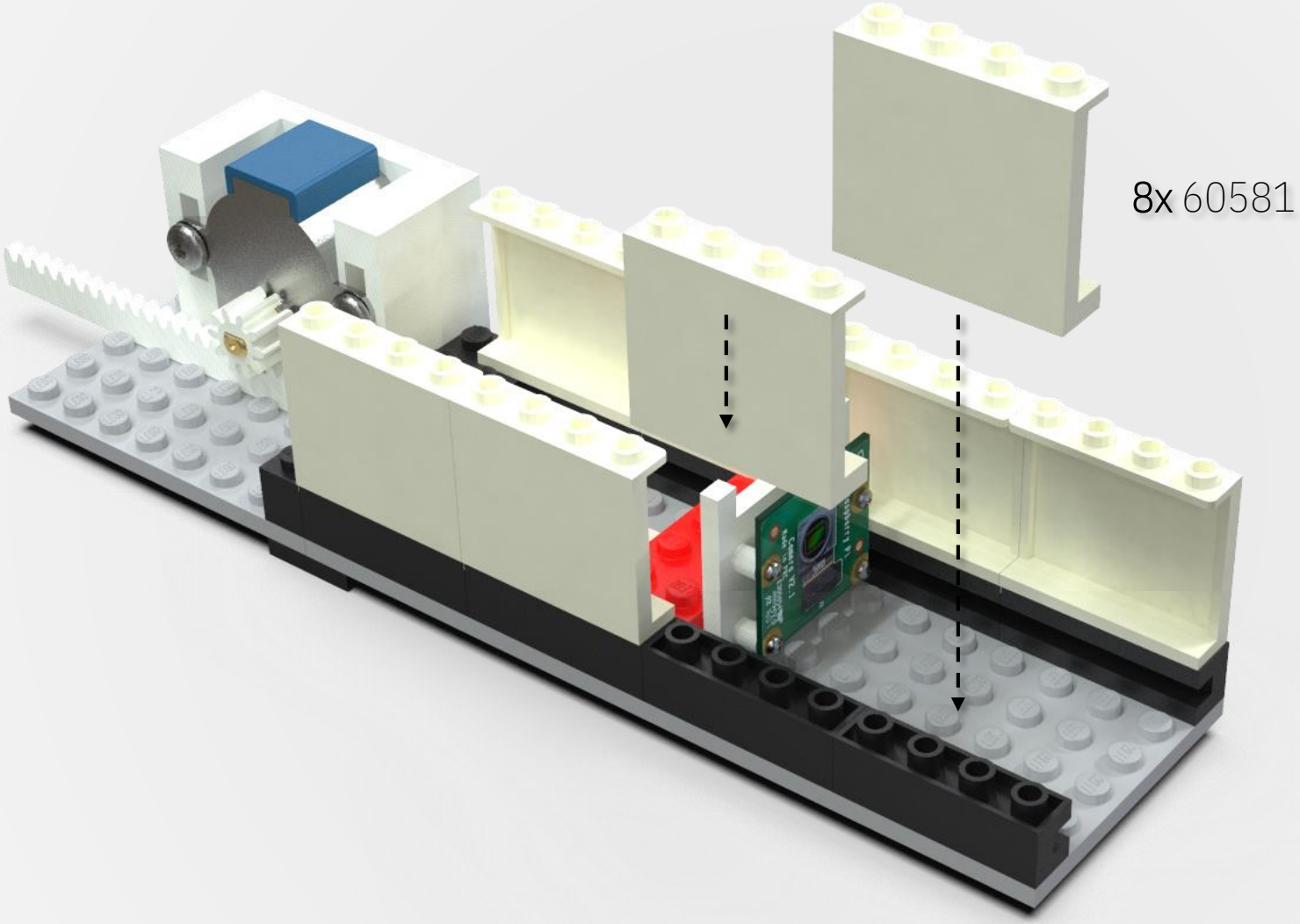
Camera module



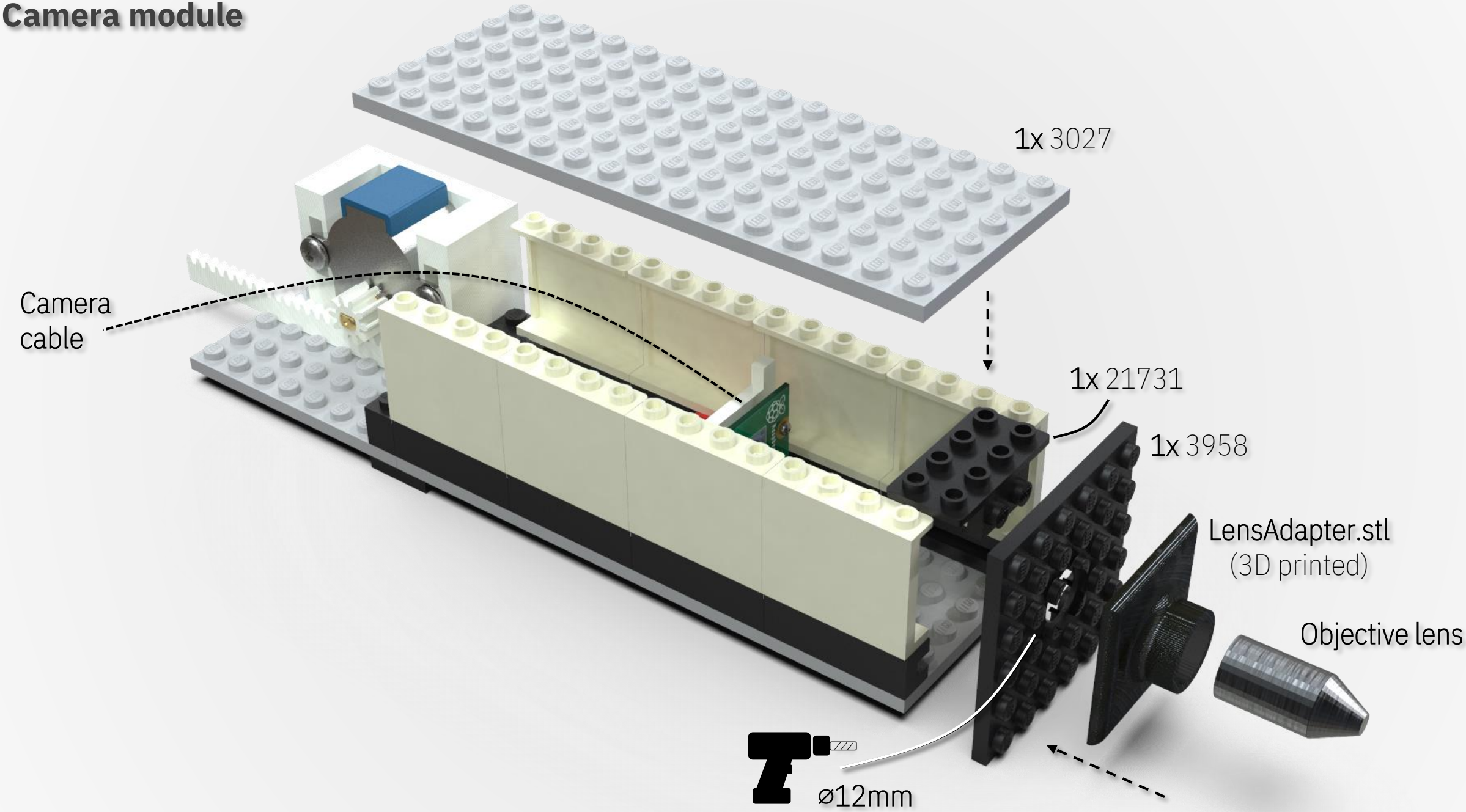
Camera module



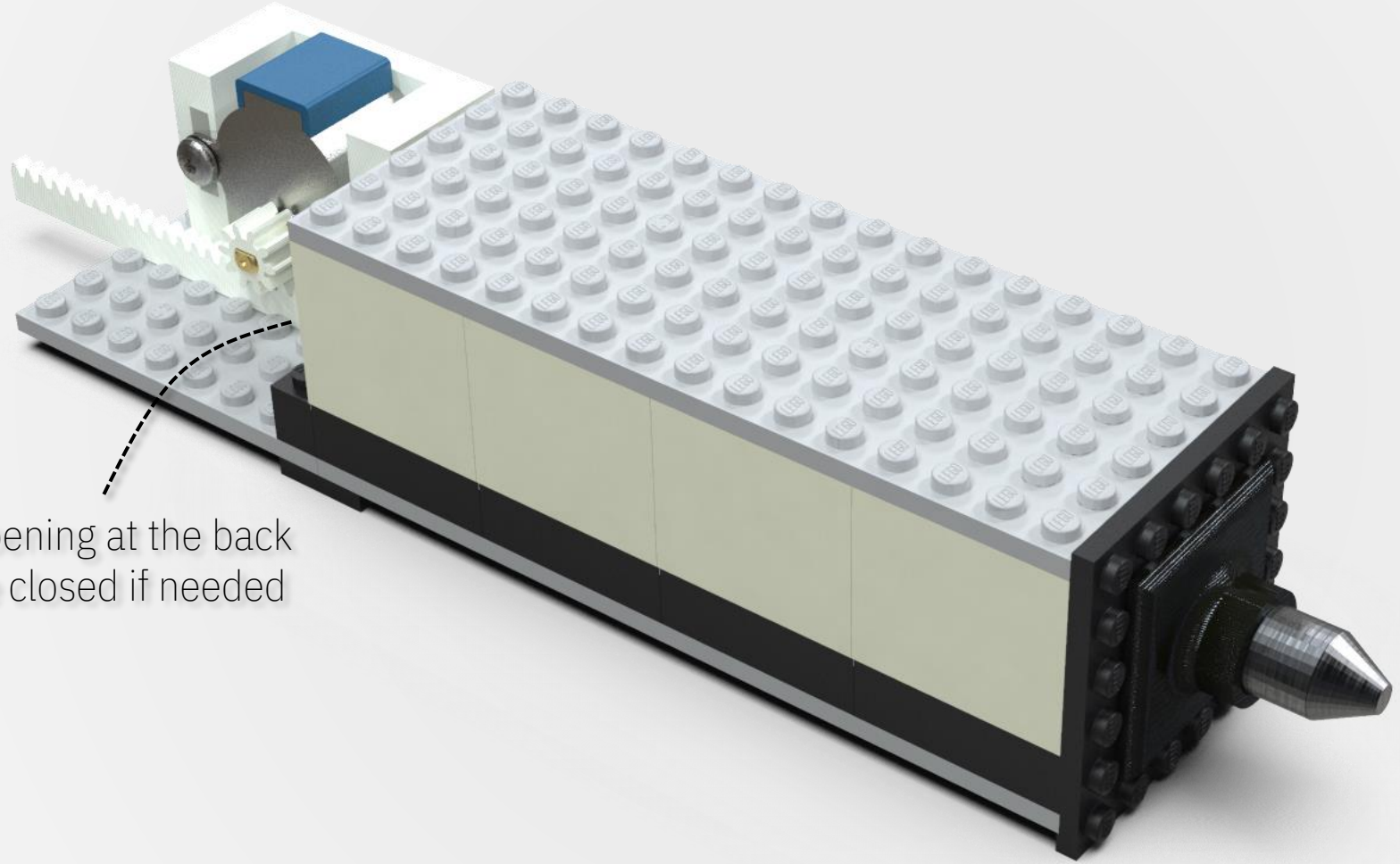
Camera module



Camera module

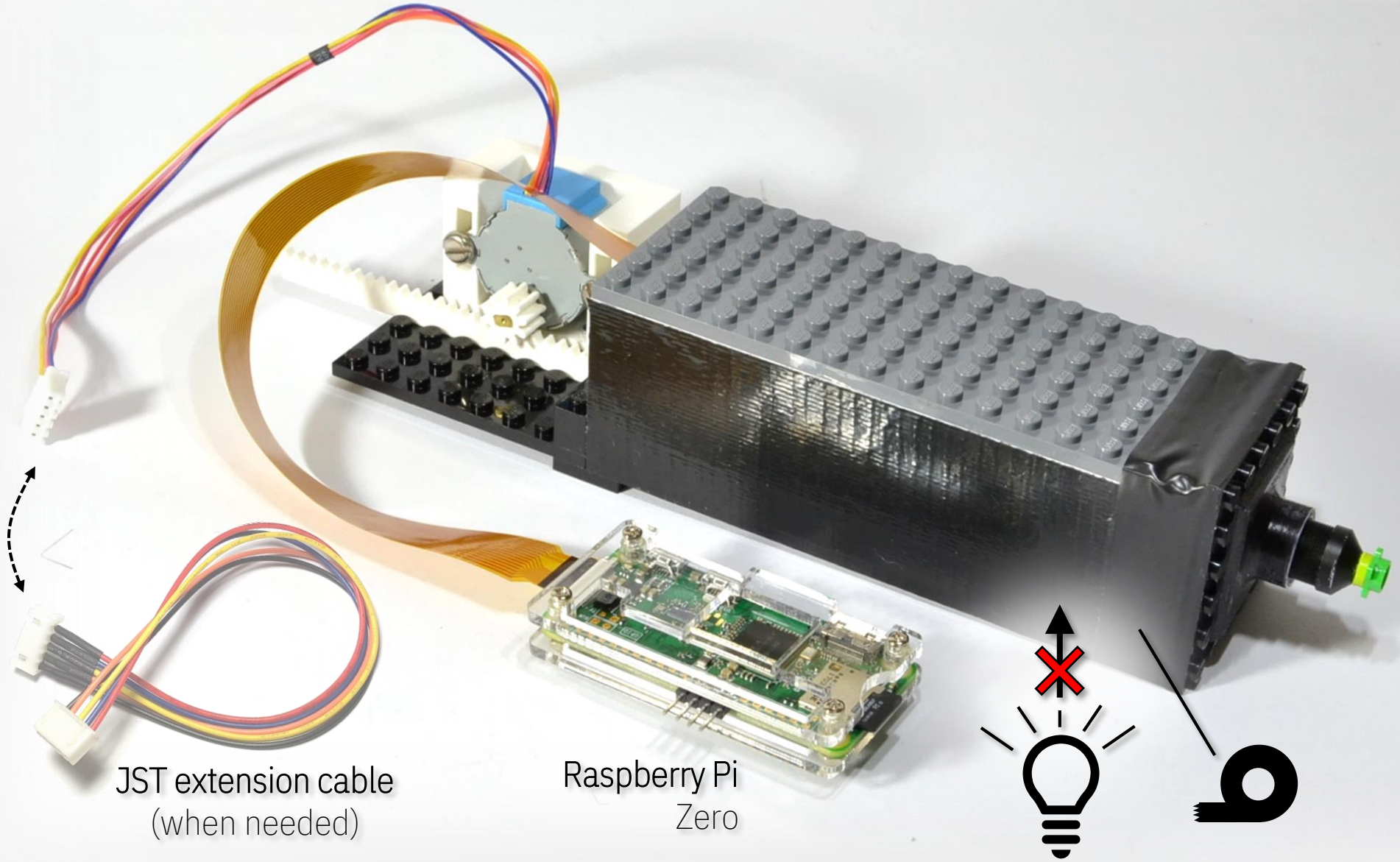


Camera module



Camera module

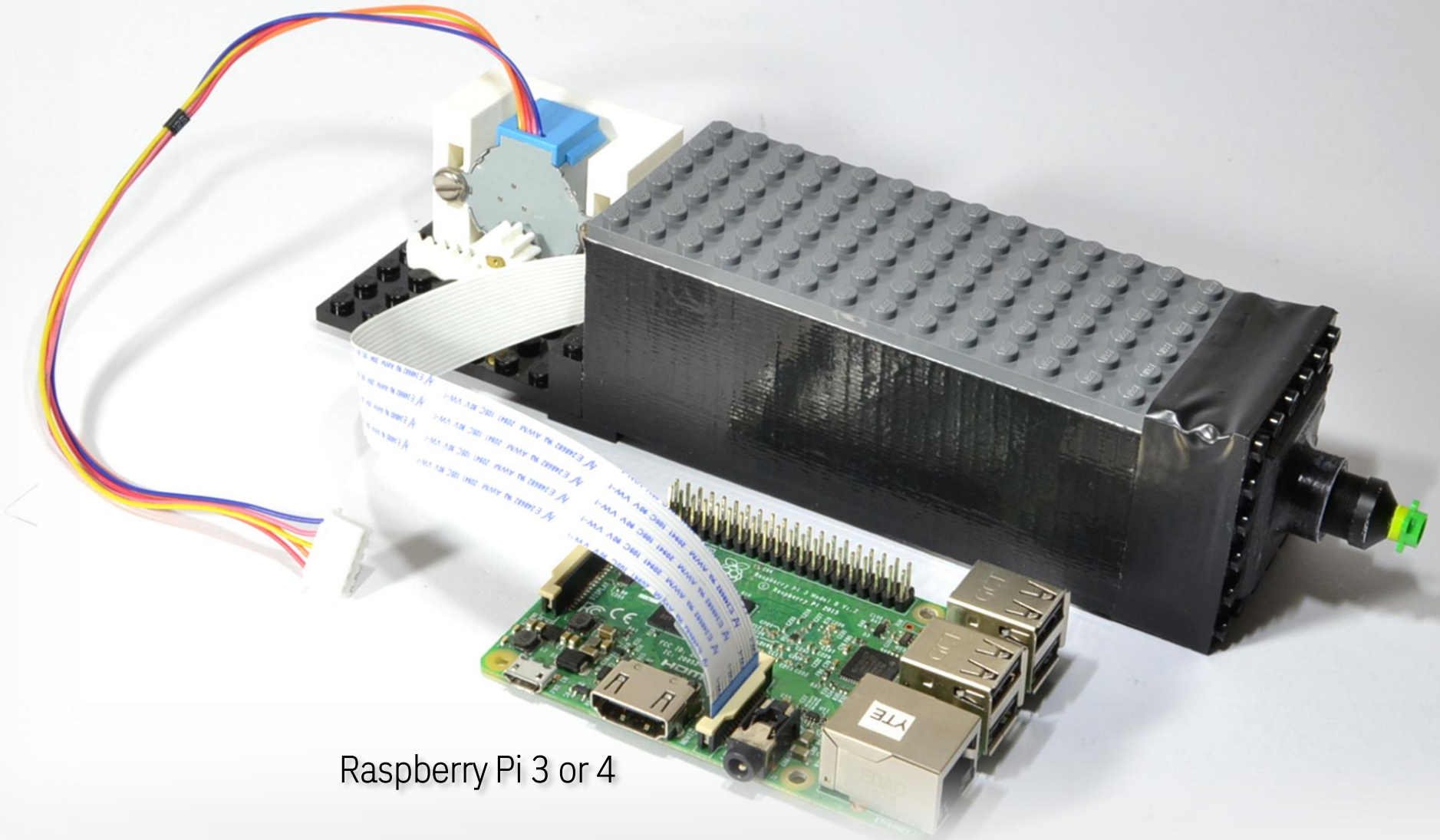
(Photograph)



Smaller aperture
(when needed)

Camera module

(Photograph)



Raspberry Pi 3 or 4

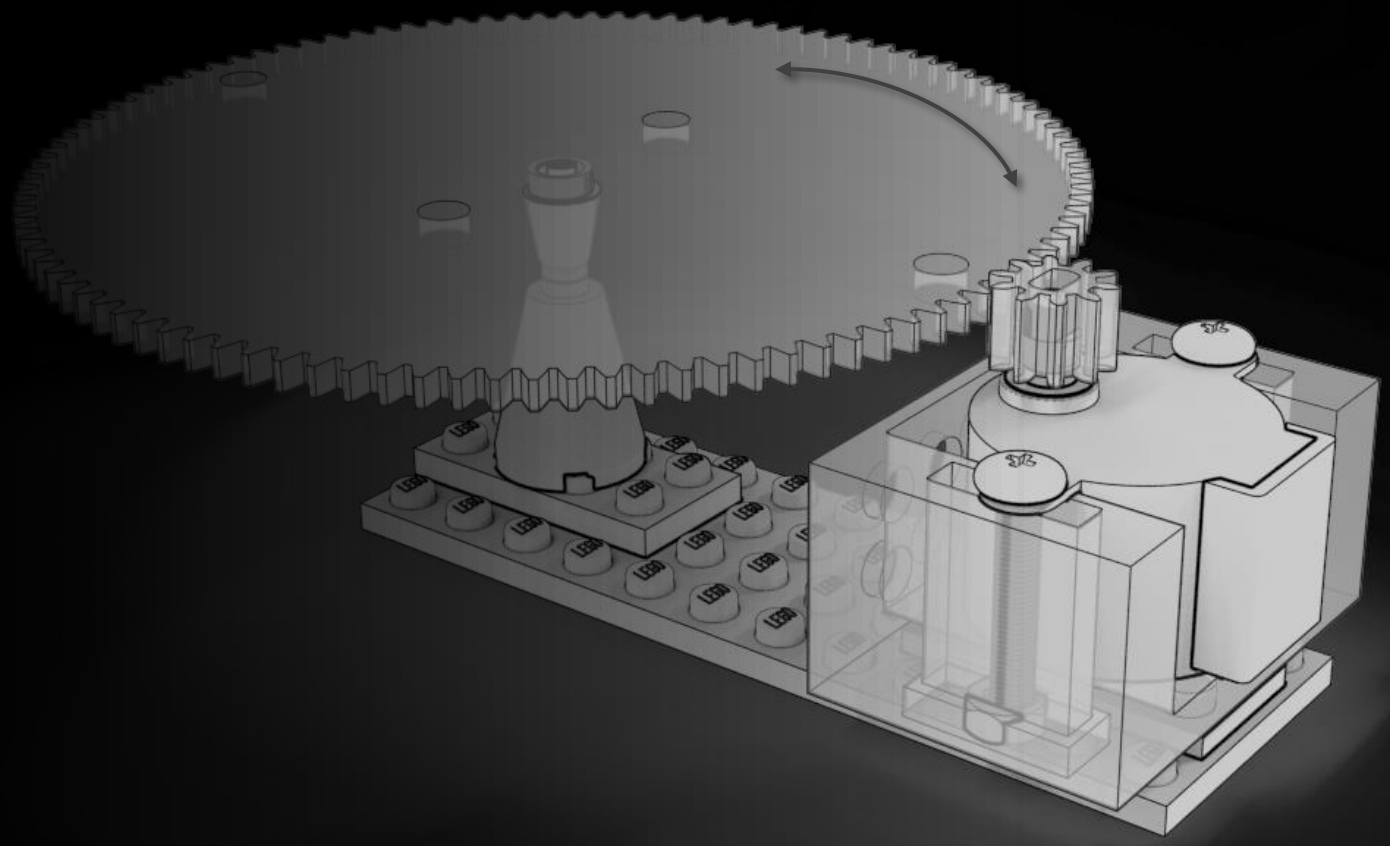
Camera module

(Photograph)

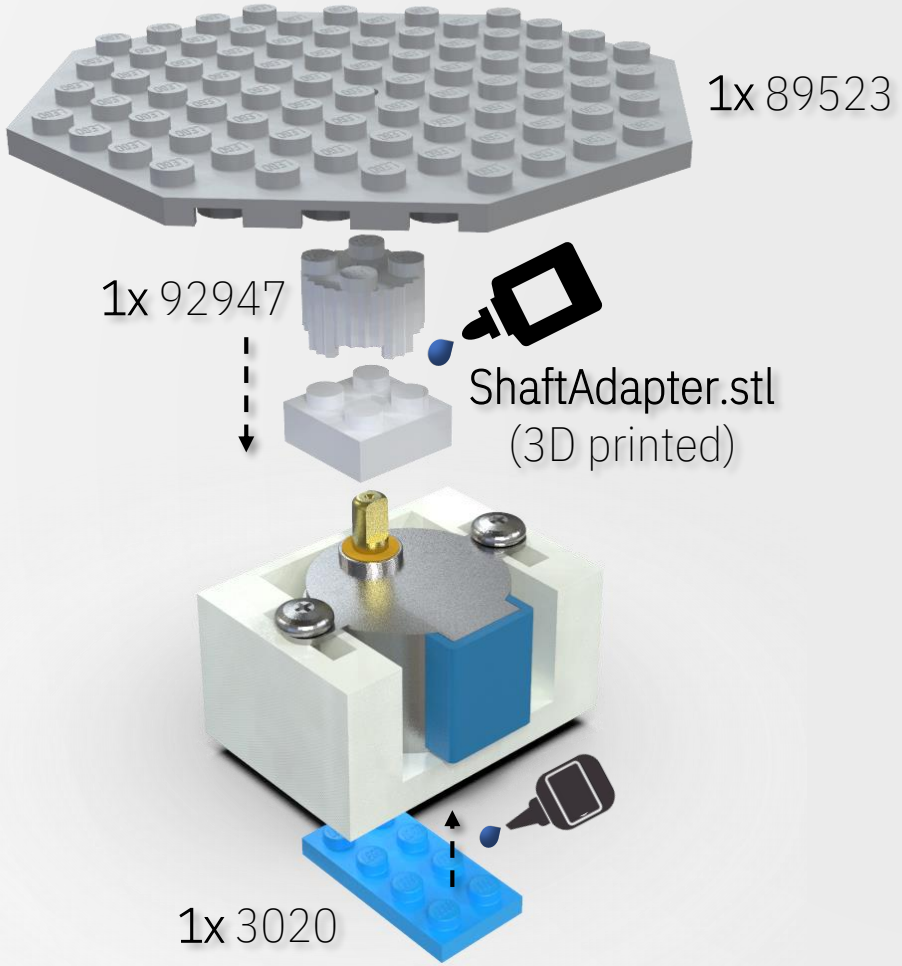
TREEYE 15.3mm
magnifying lens

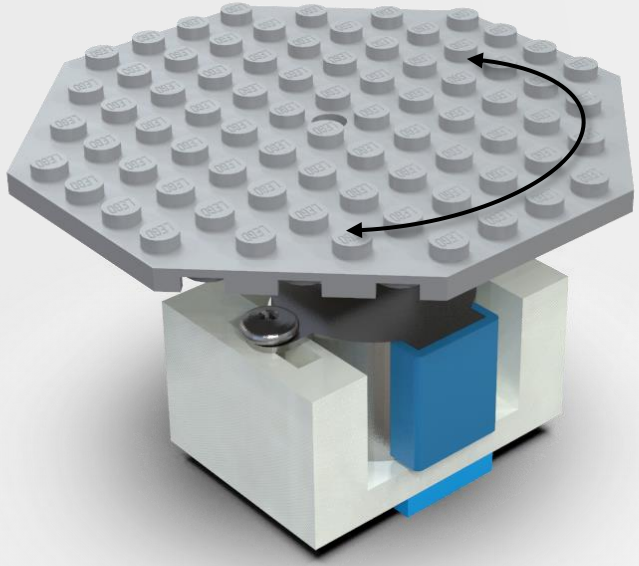
TREEYE M12 lens holder
(alternative to the
3D printed adapter)

Rotary stage

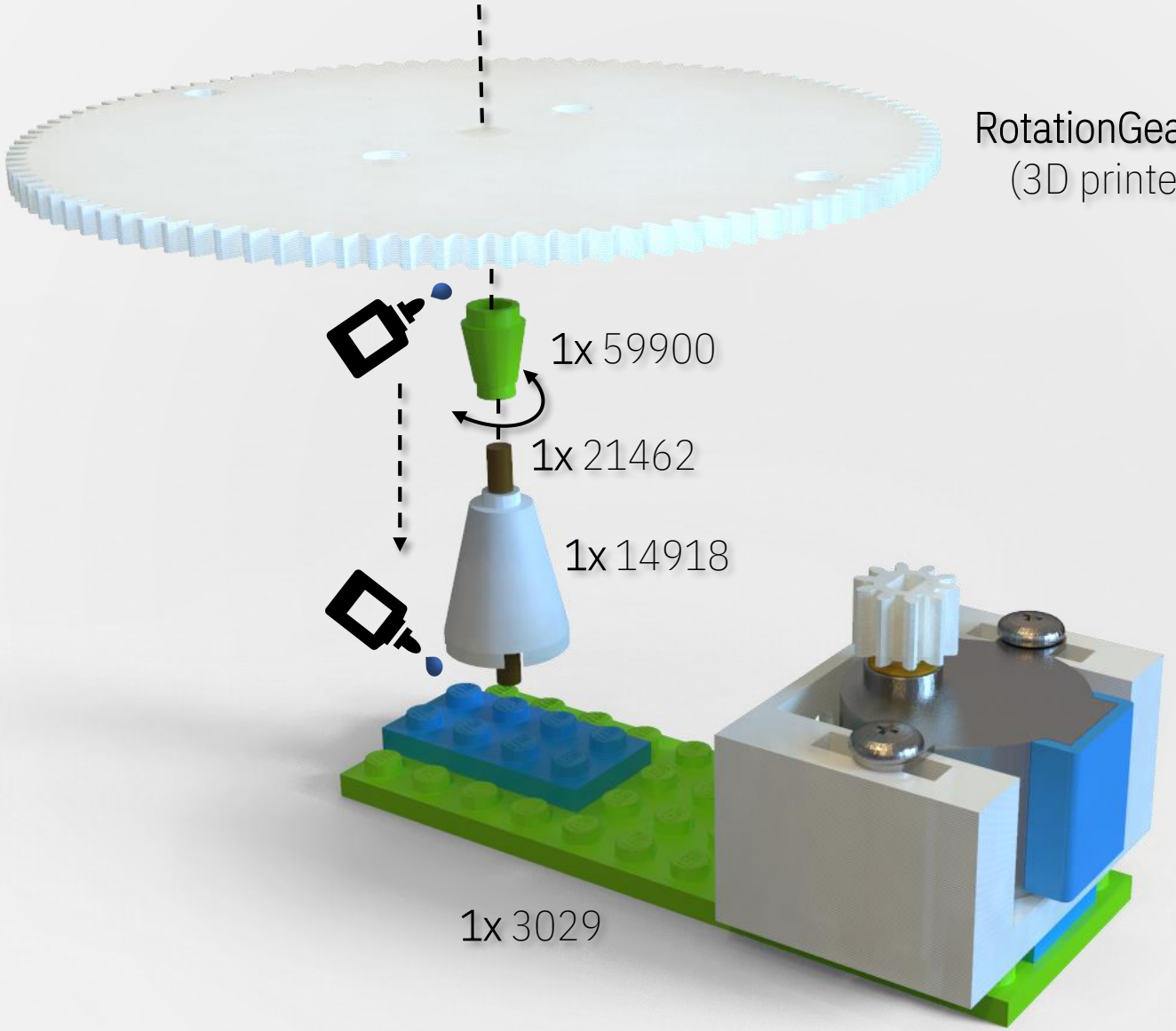


Rotary stage – Option 1 (simple)

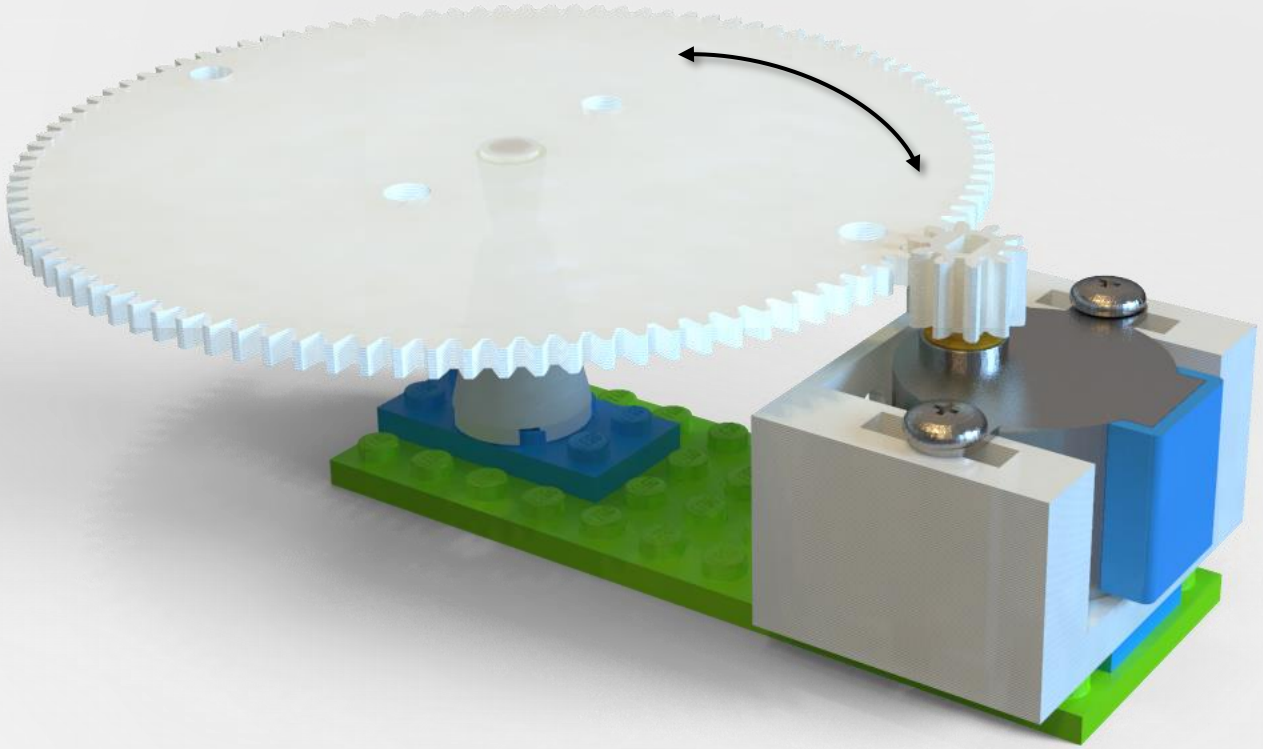




Rotary stage – Option 2 (precise)

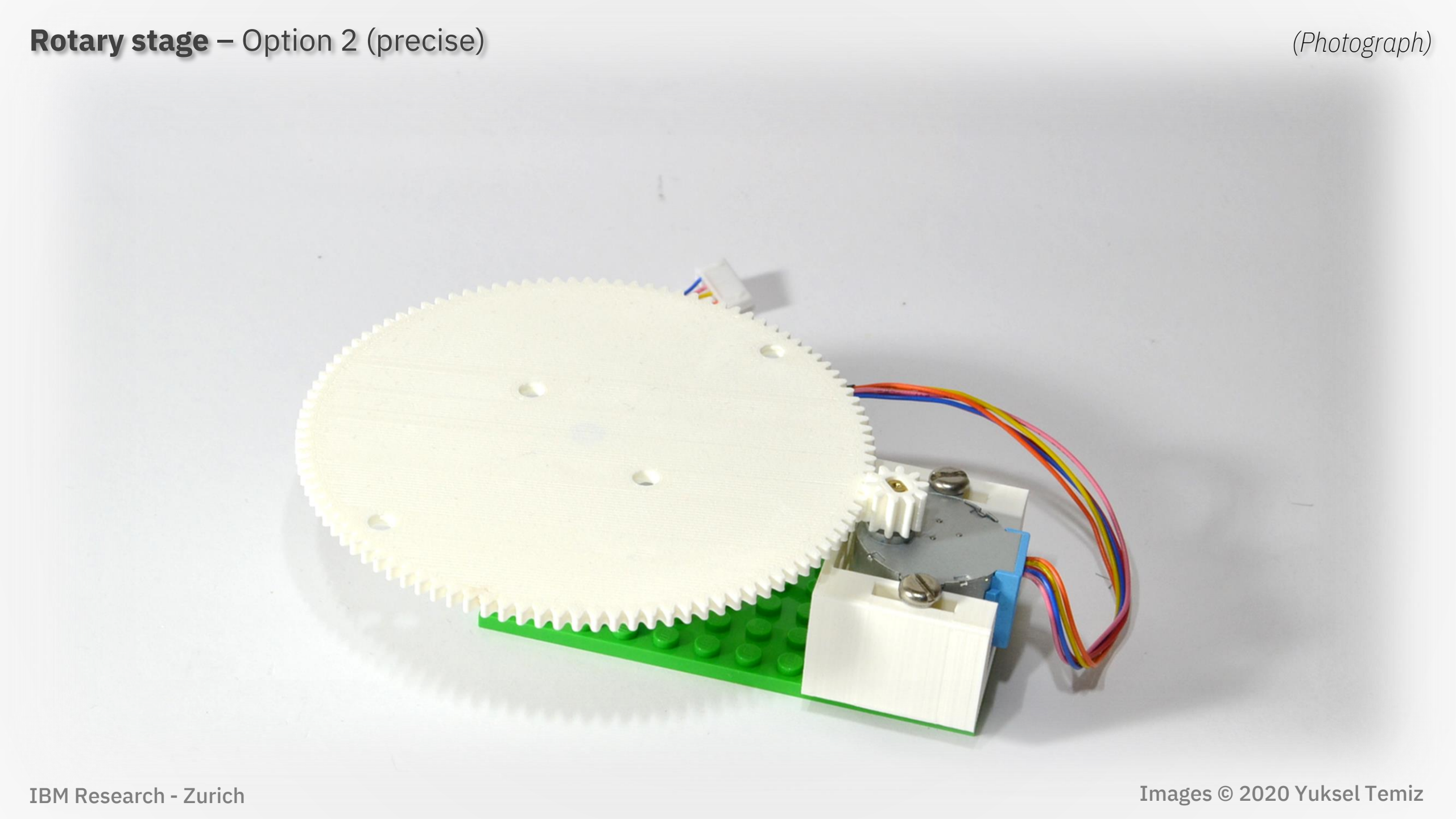


Rotary stage – Option 2 (precise)

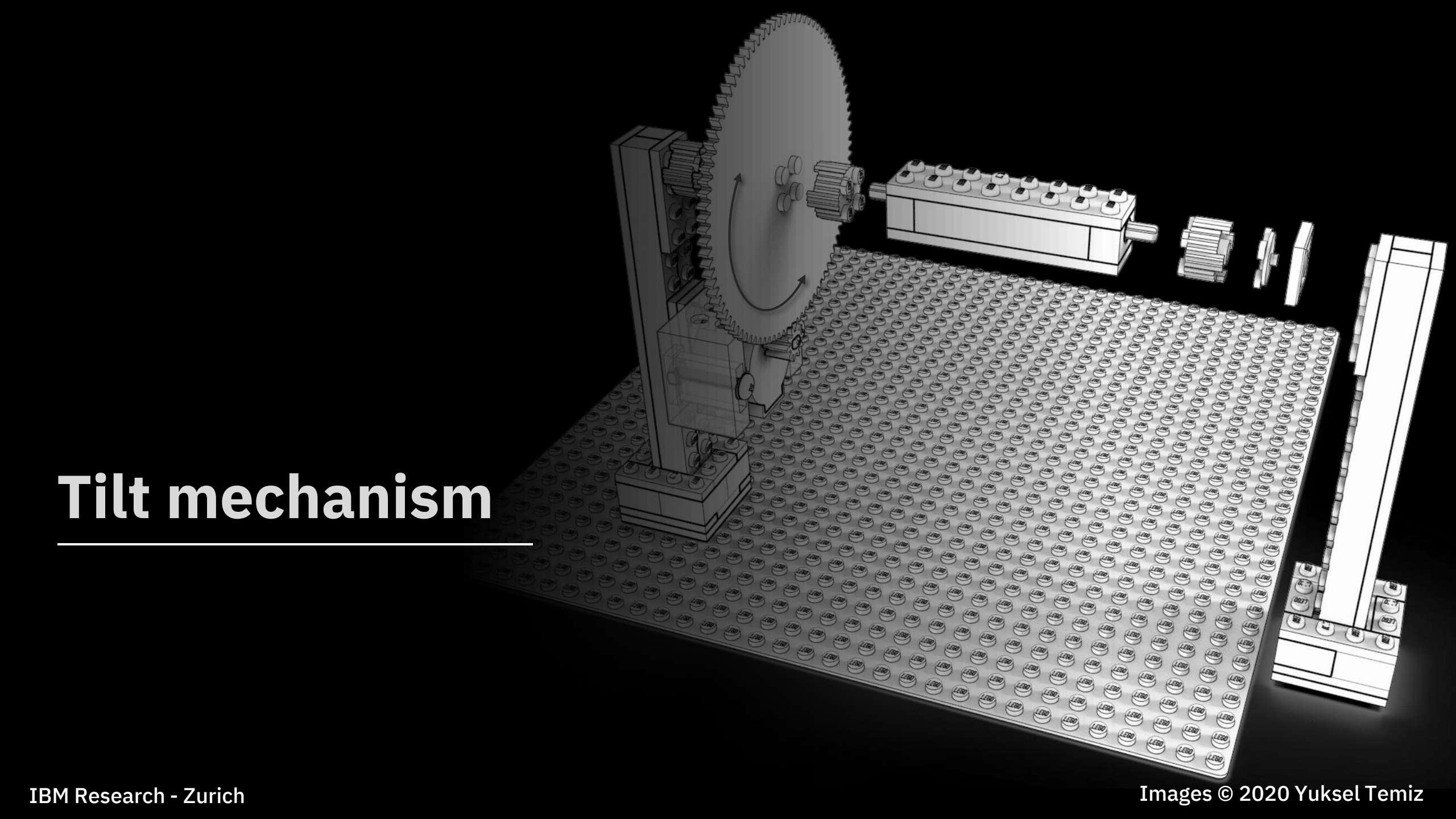


Rotary stage – Option 2 (precise)

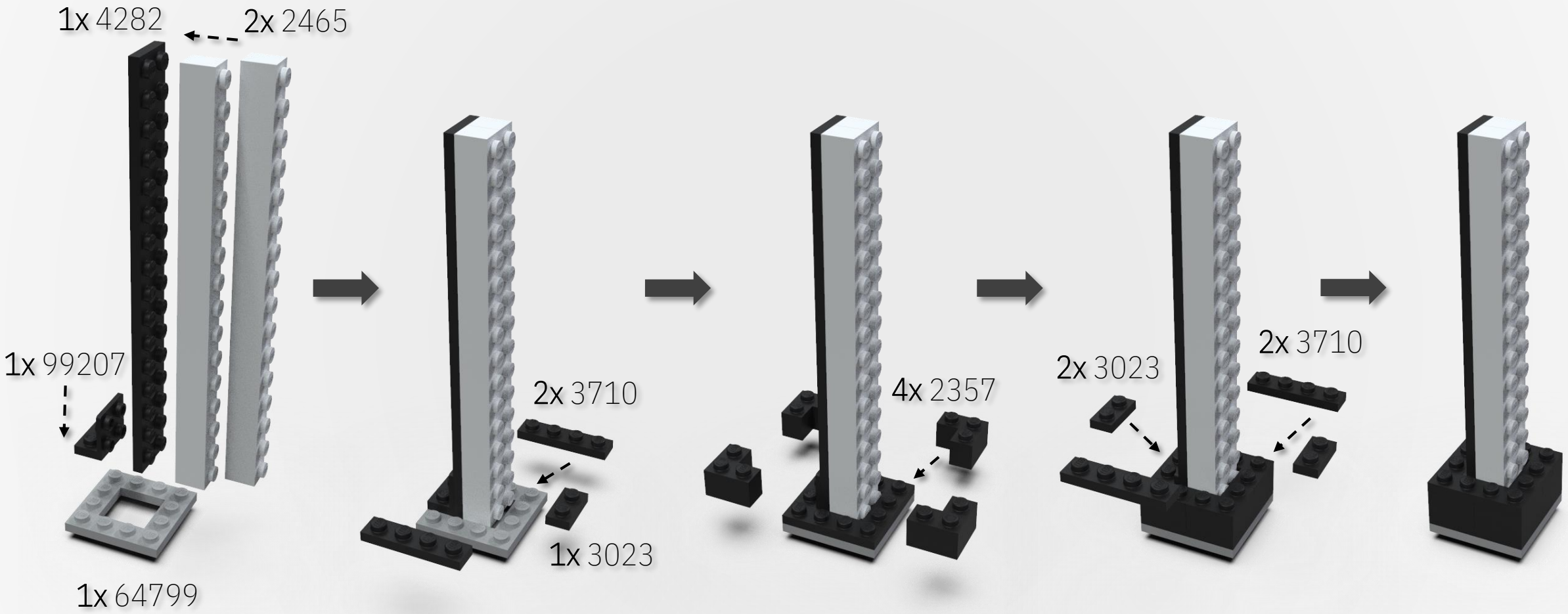
(Photograph)



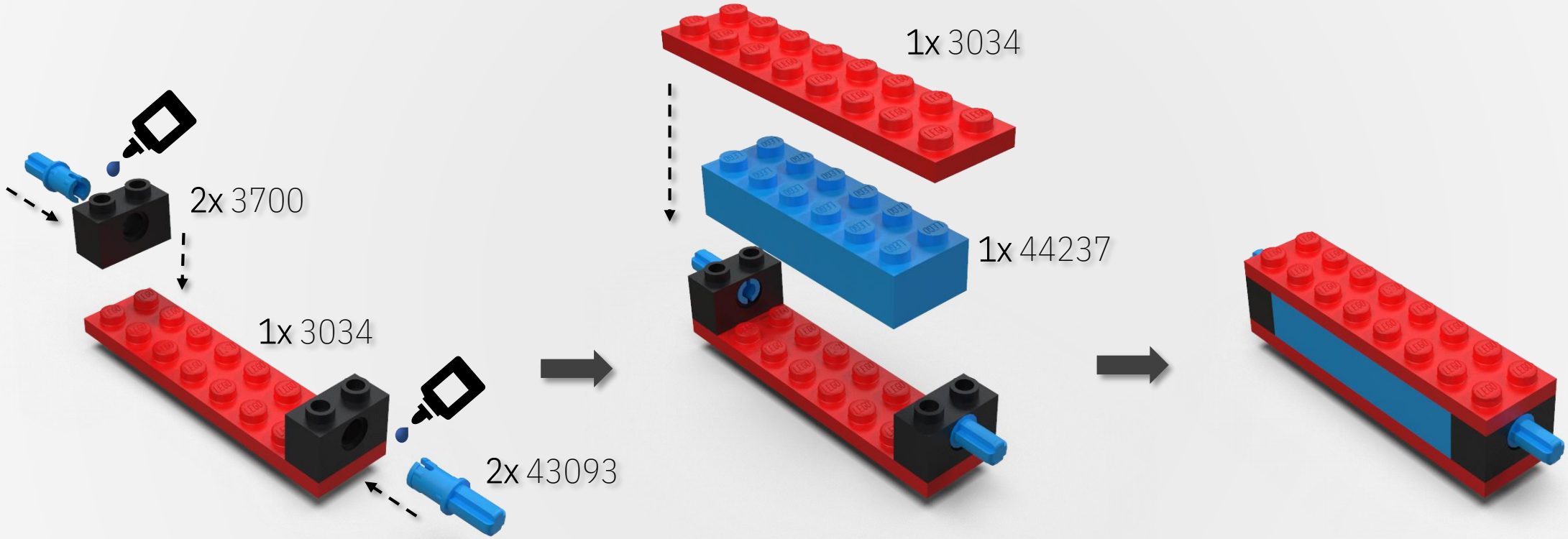
Tilt mechanism



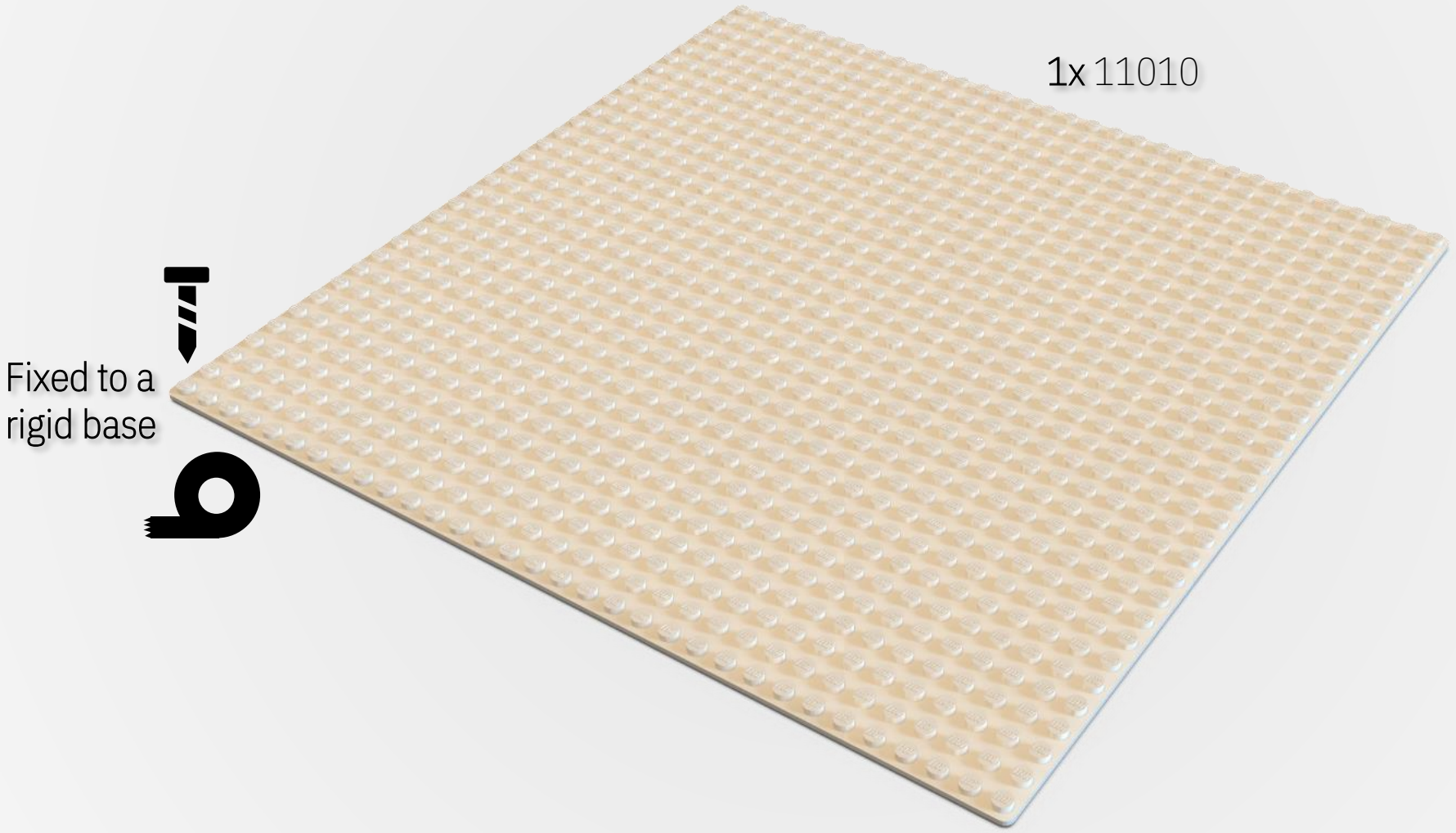
Tilt mechanism – Vertical supports



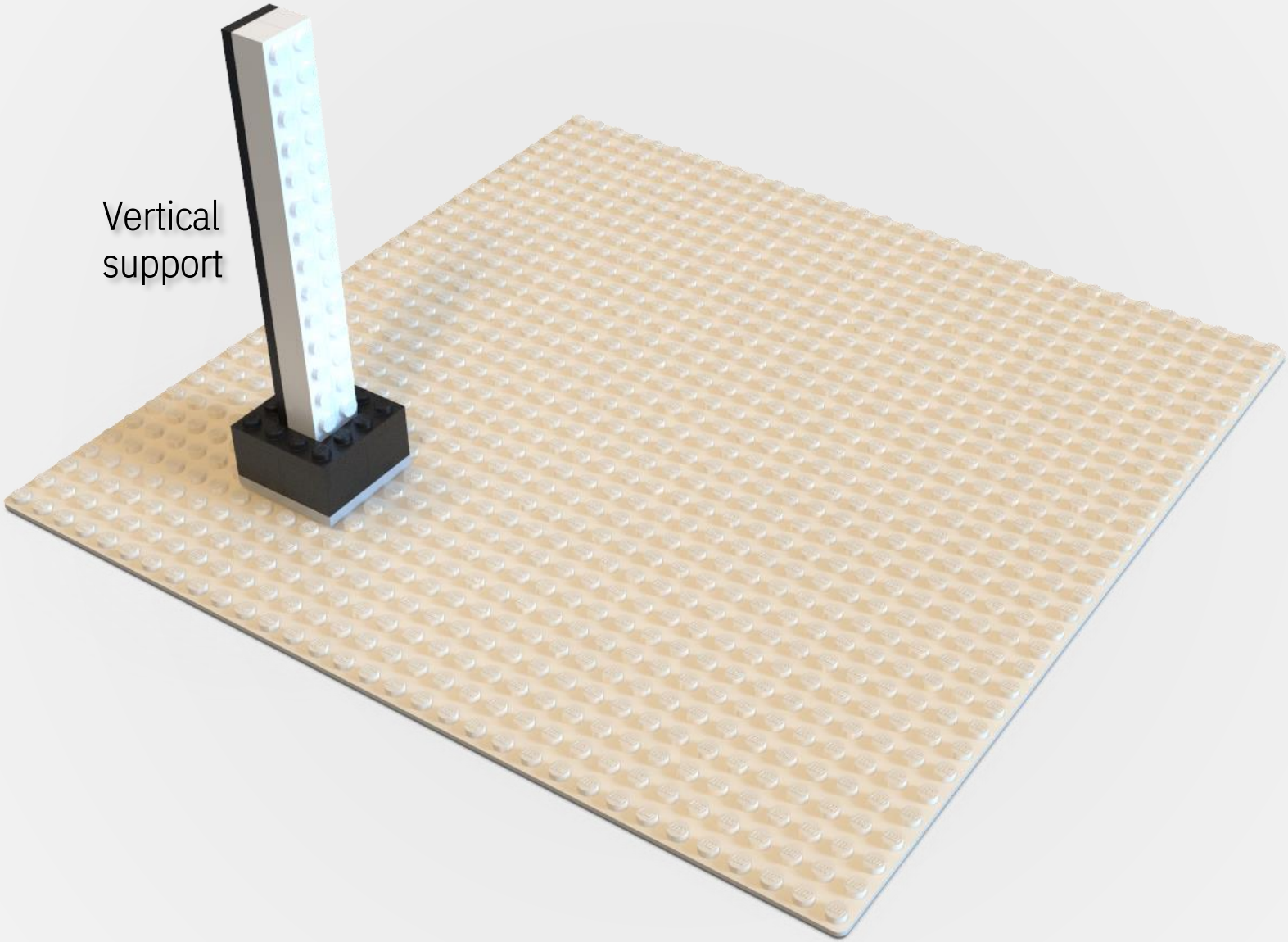
Tilt mechanism – Camera stage



Tilt mechanism



Tilt mechanism



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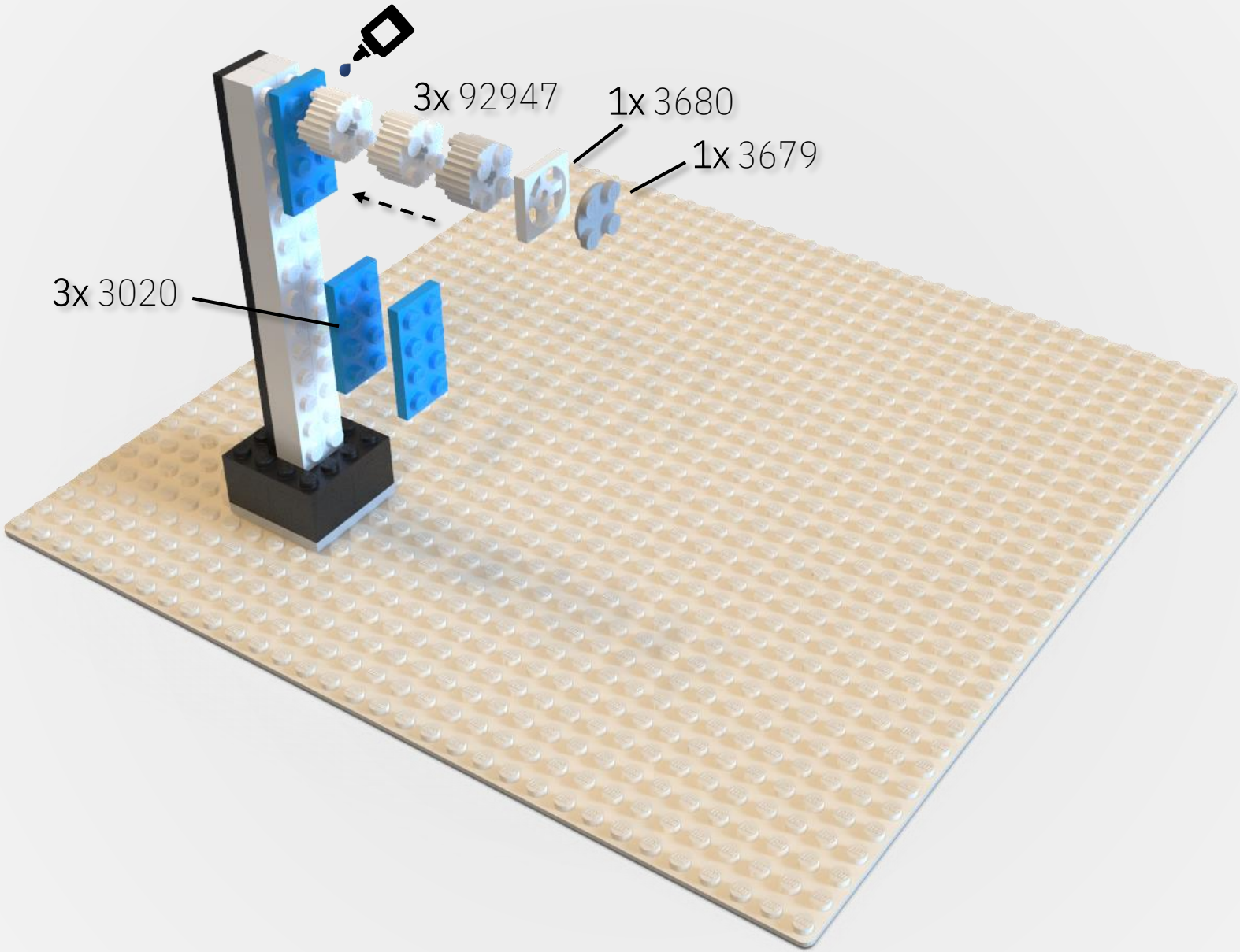

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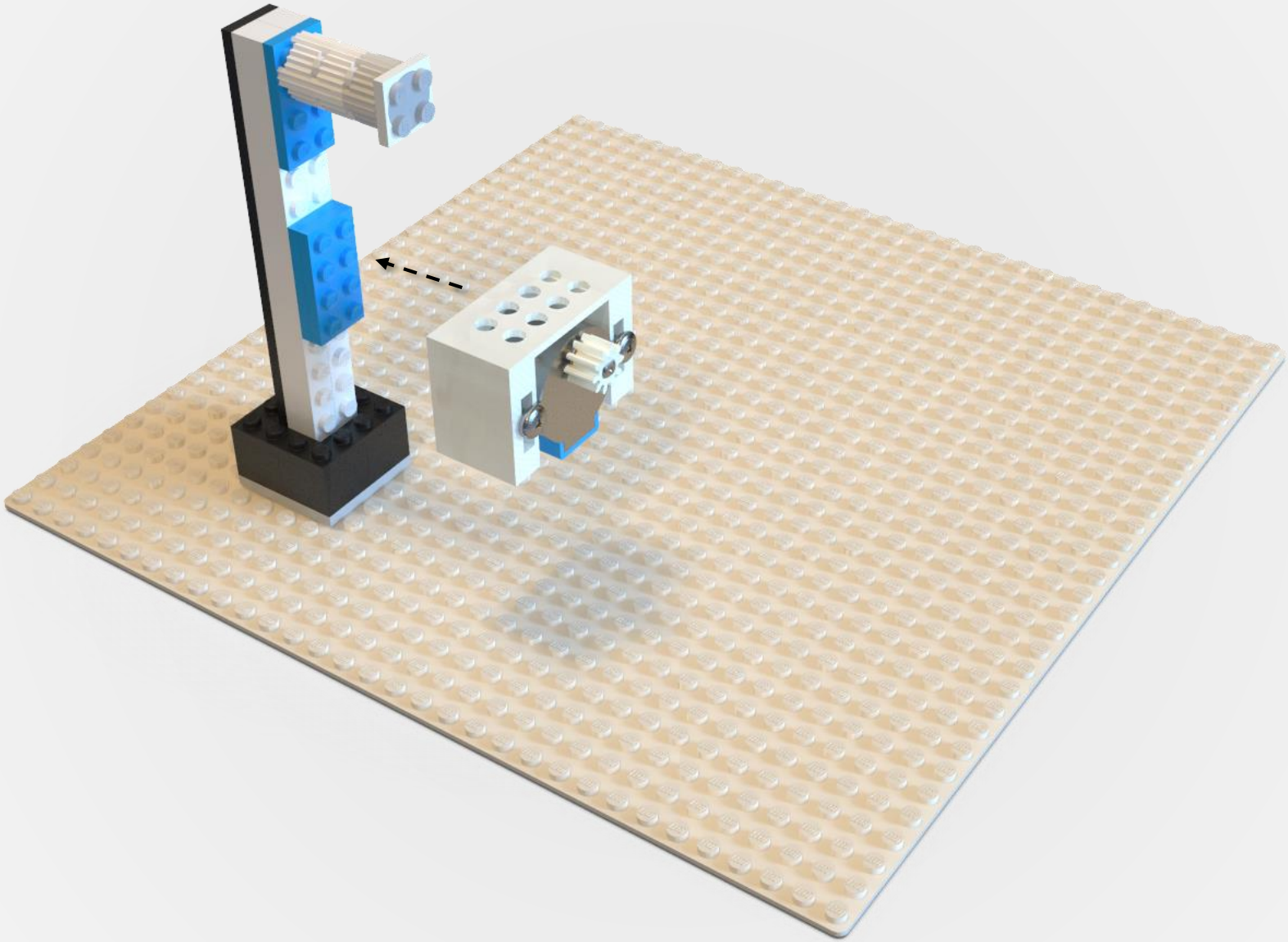

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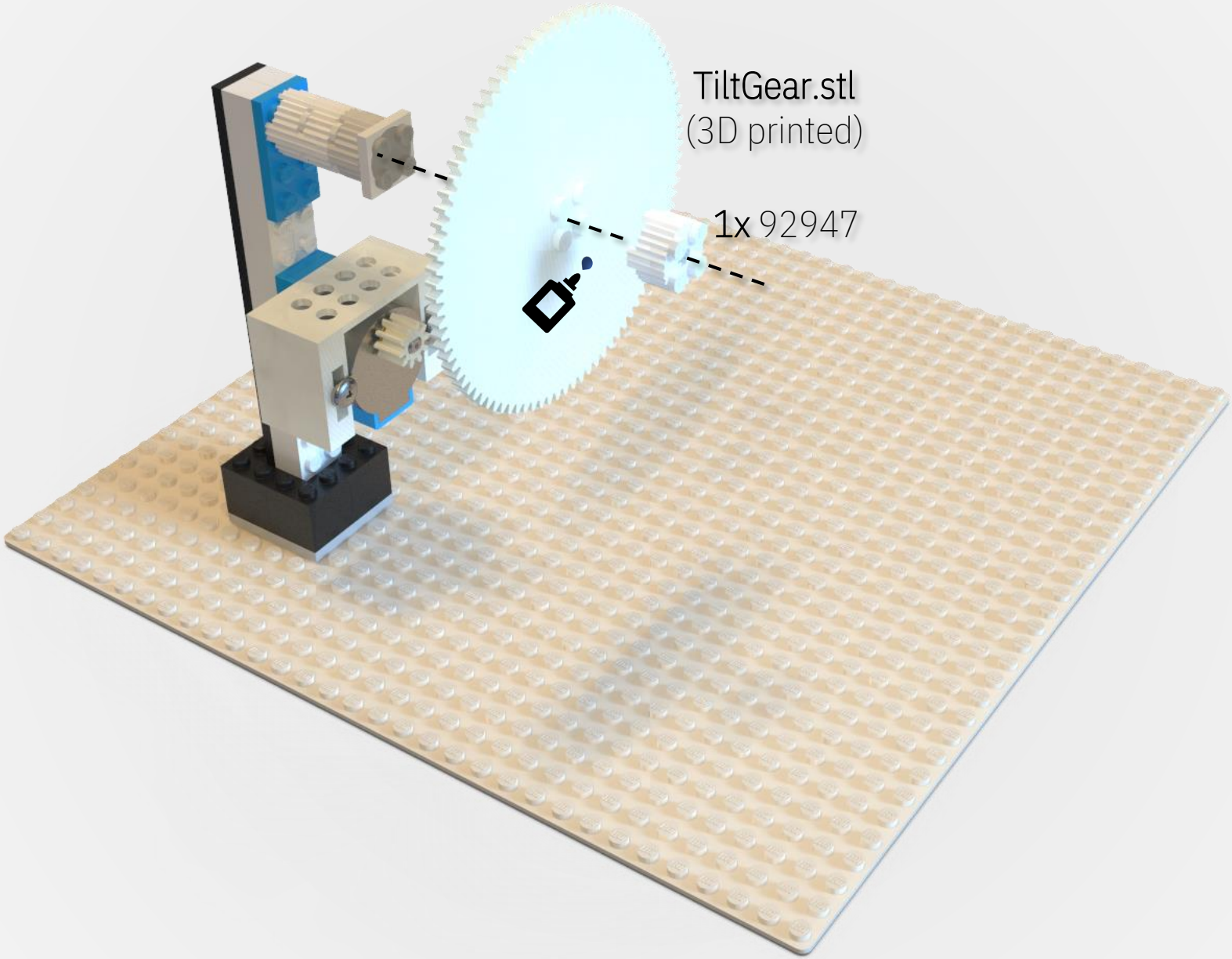
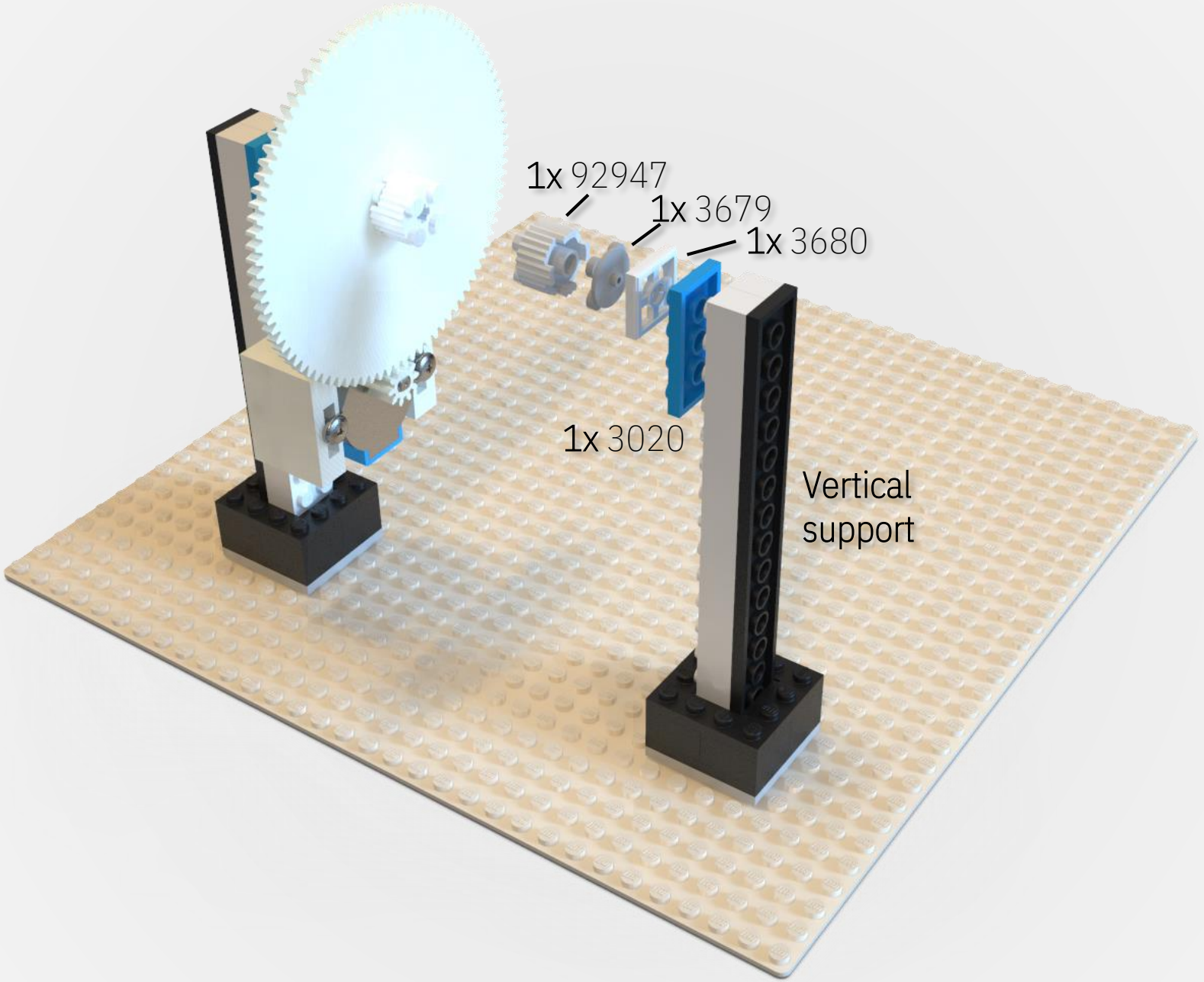


Tilt mechanism



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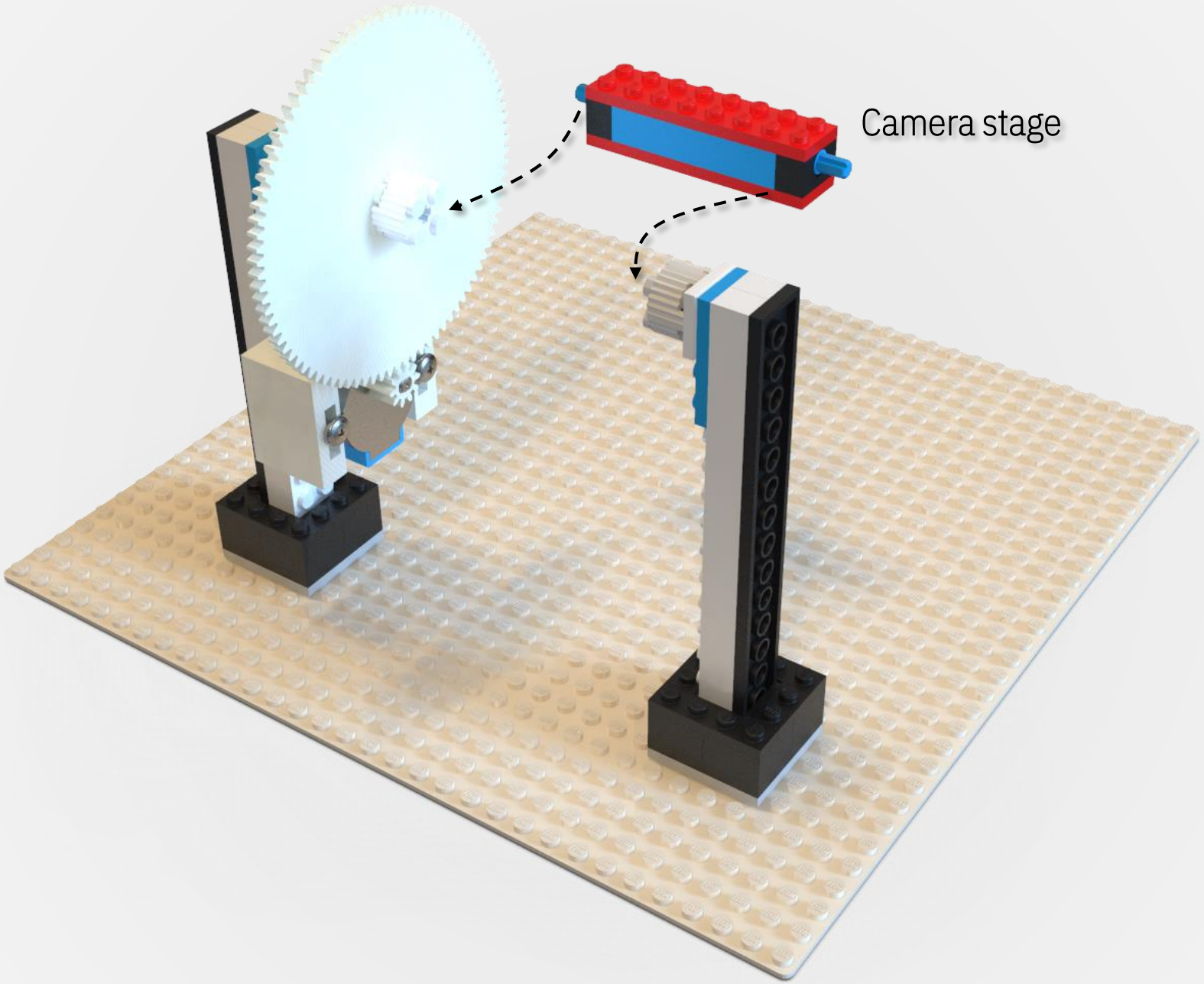

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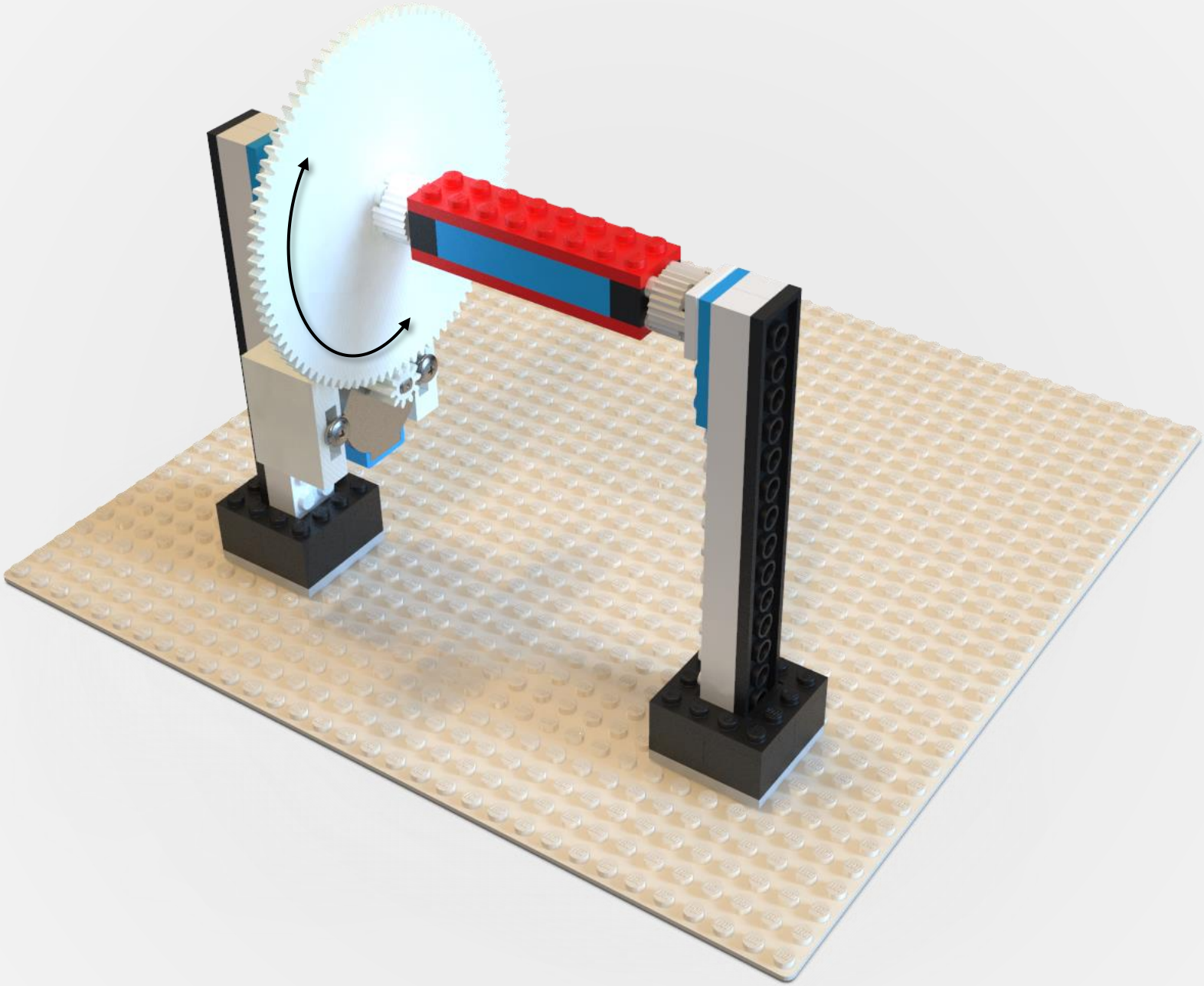
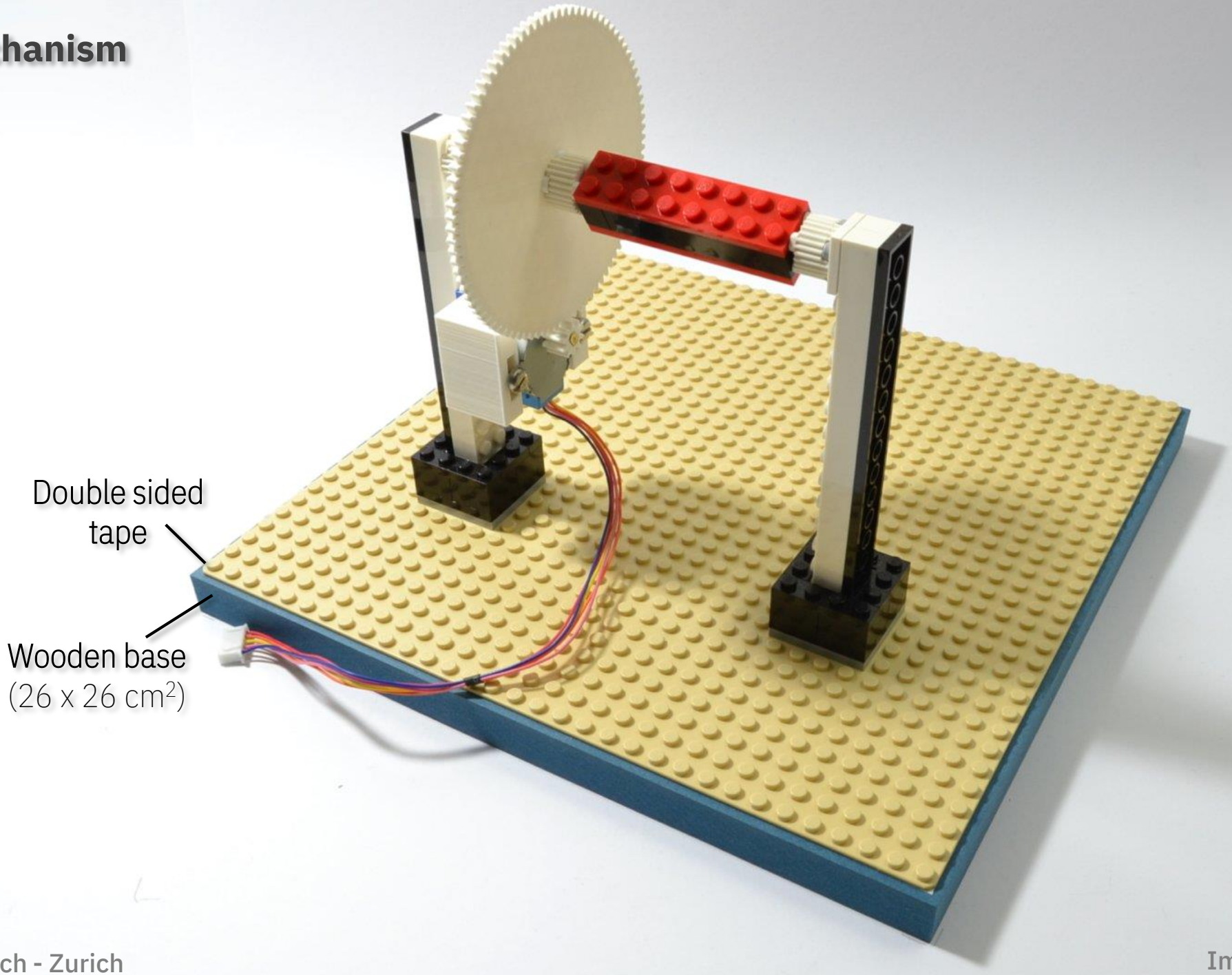
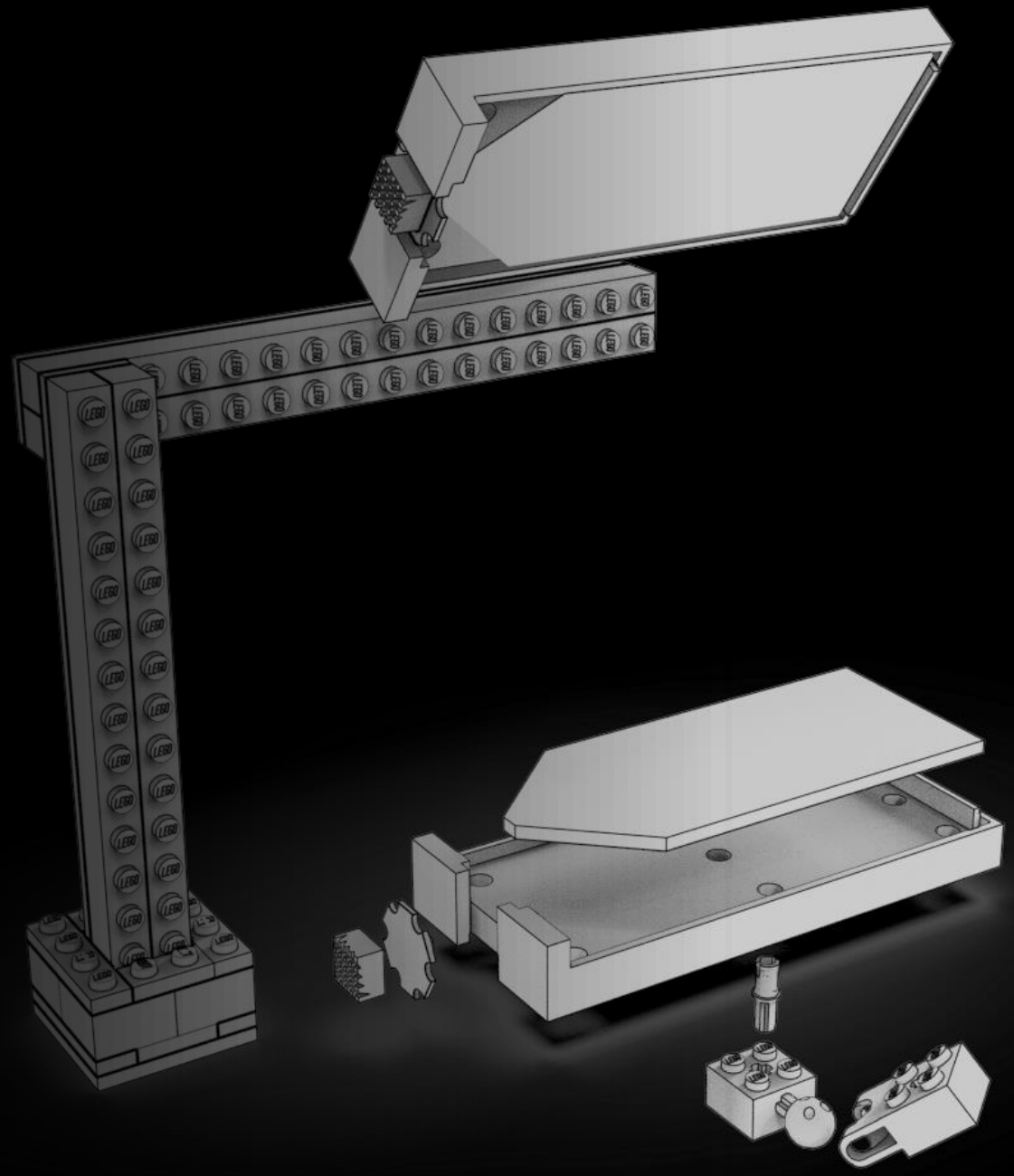


Tilt mechanism

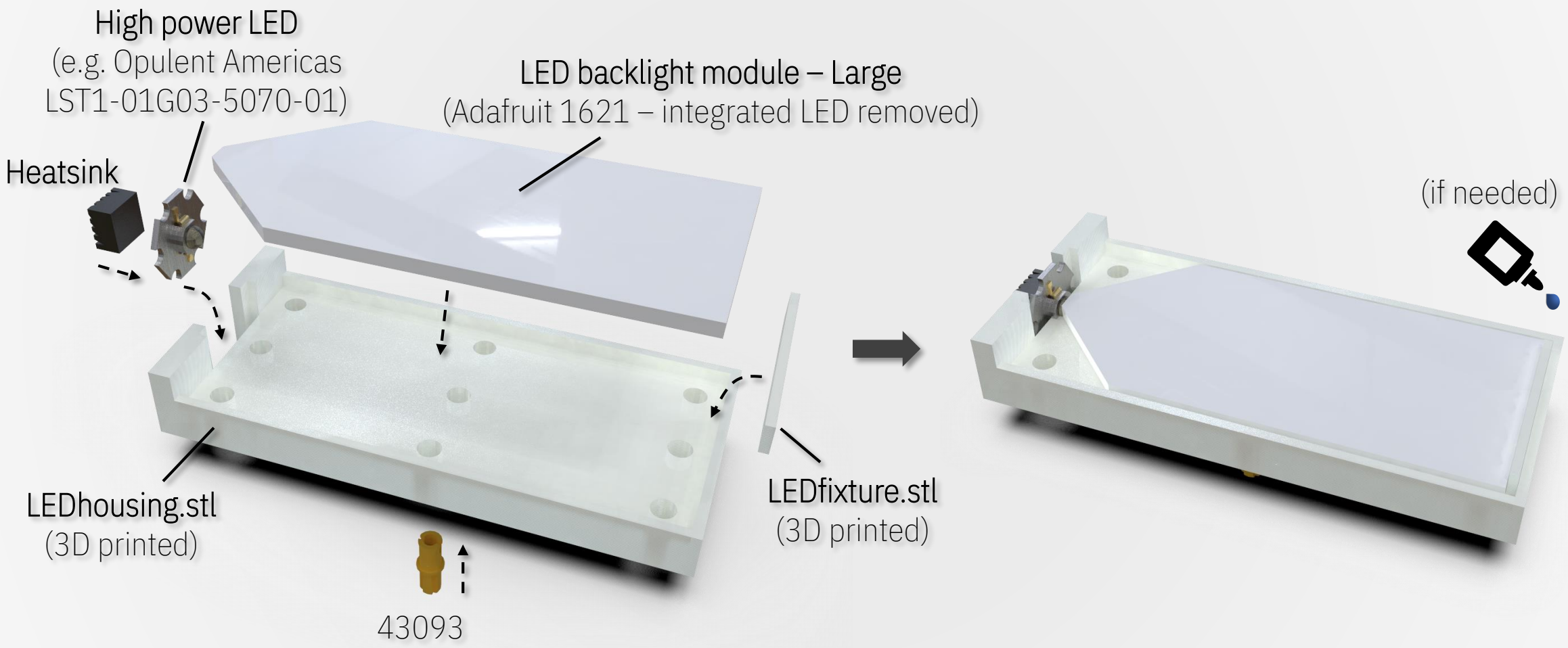
(Photograph)



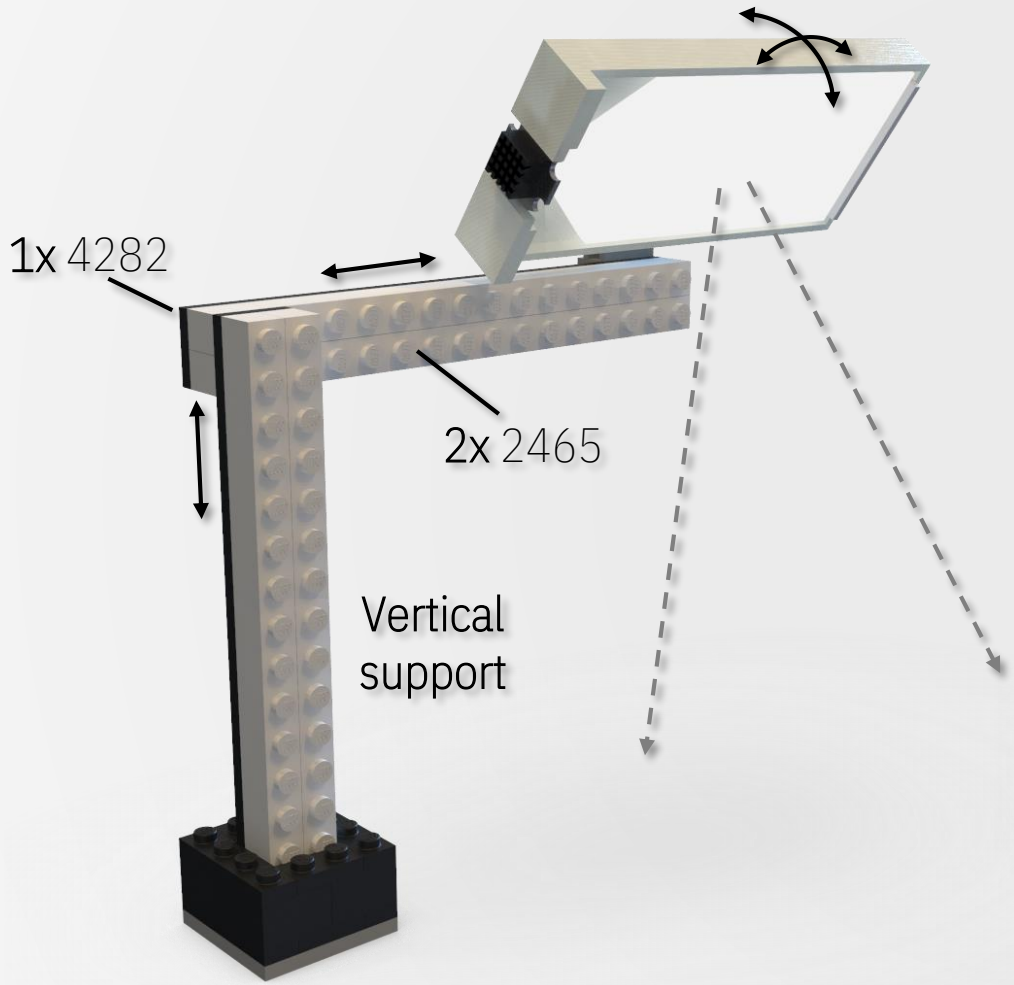
Illumination



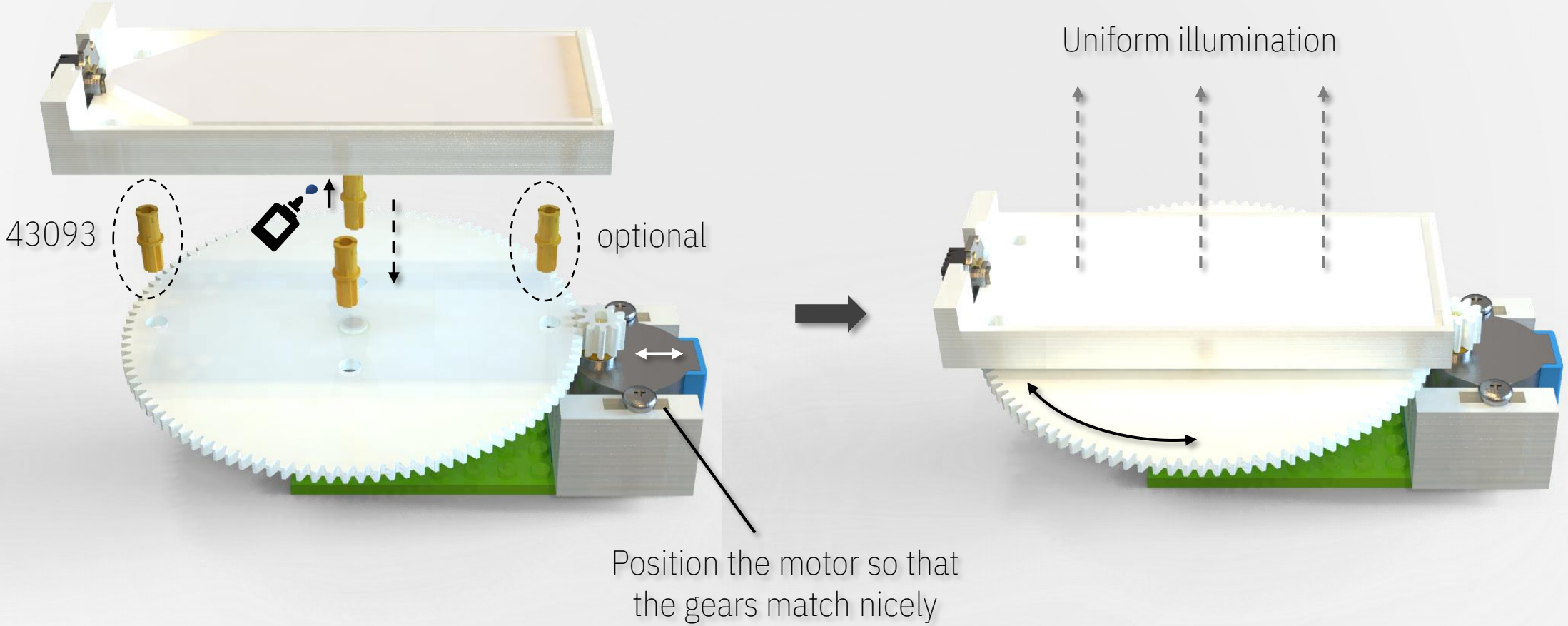
Illumination – LED diffuser



Illumination – Reflected light

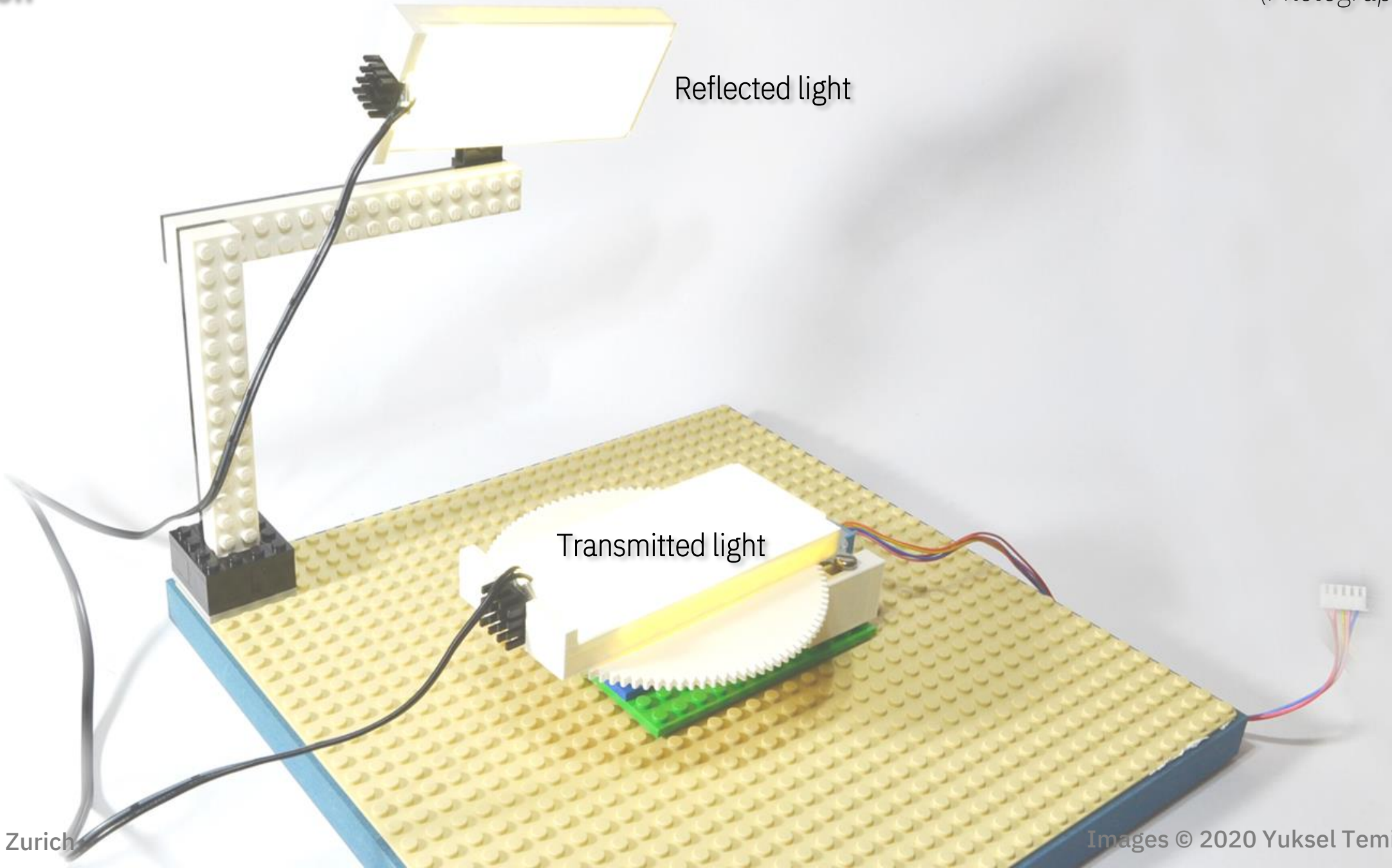


Illumination – Transmitted light

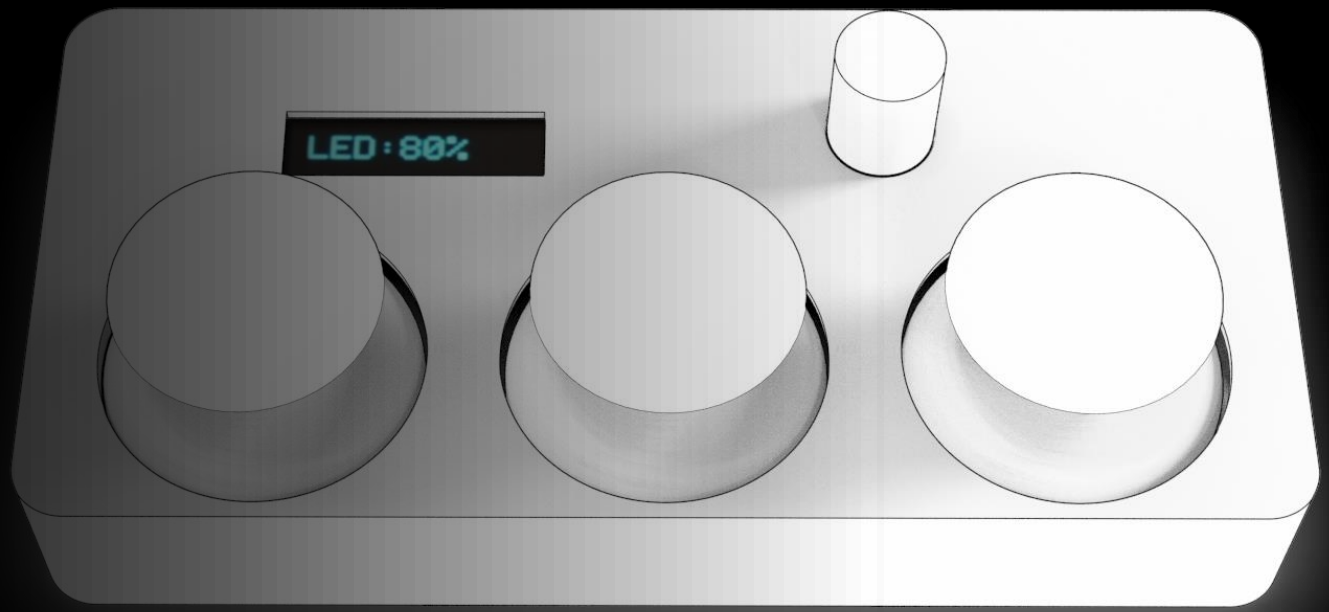


Illumination

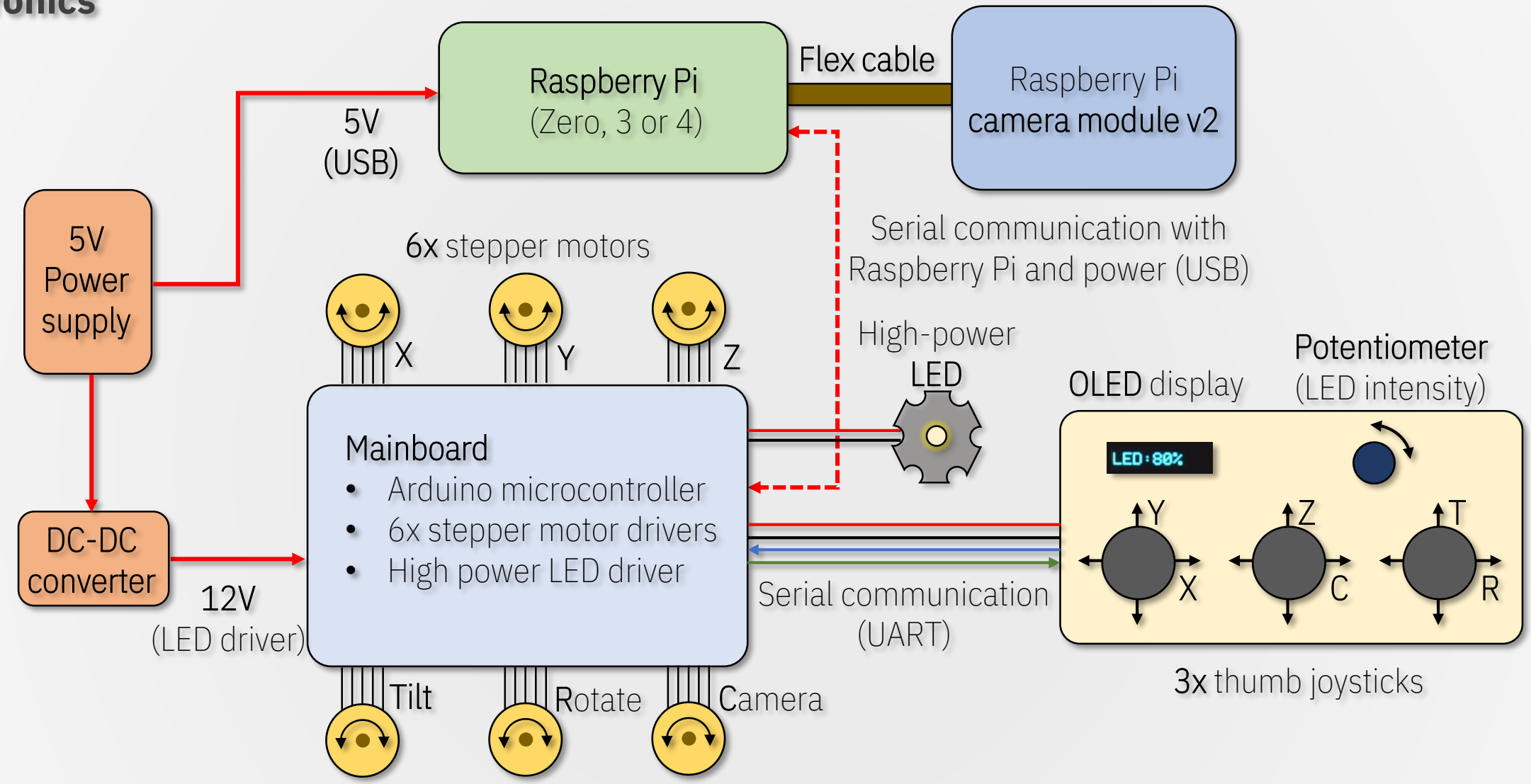
(Photograph)



Electronics



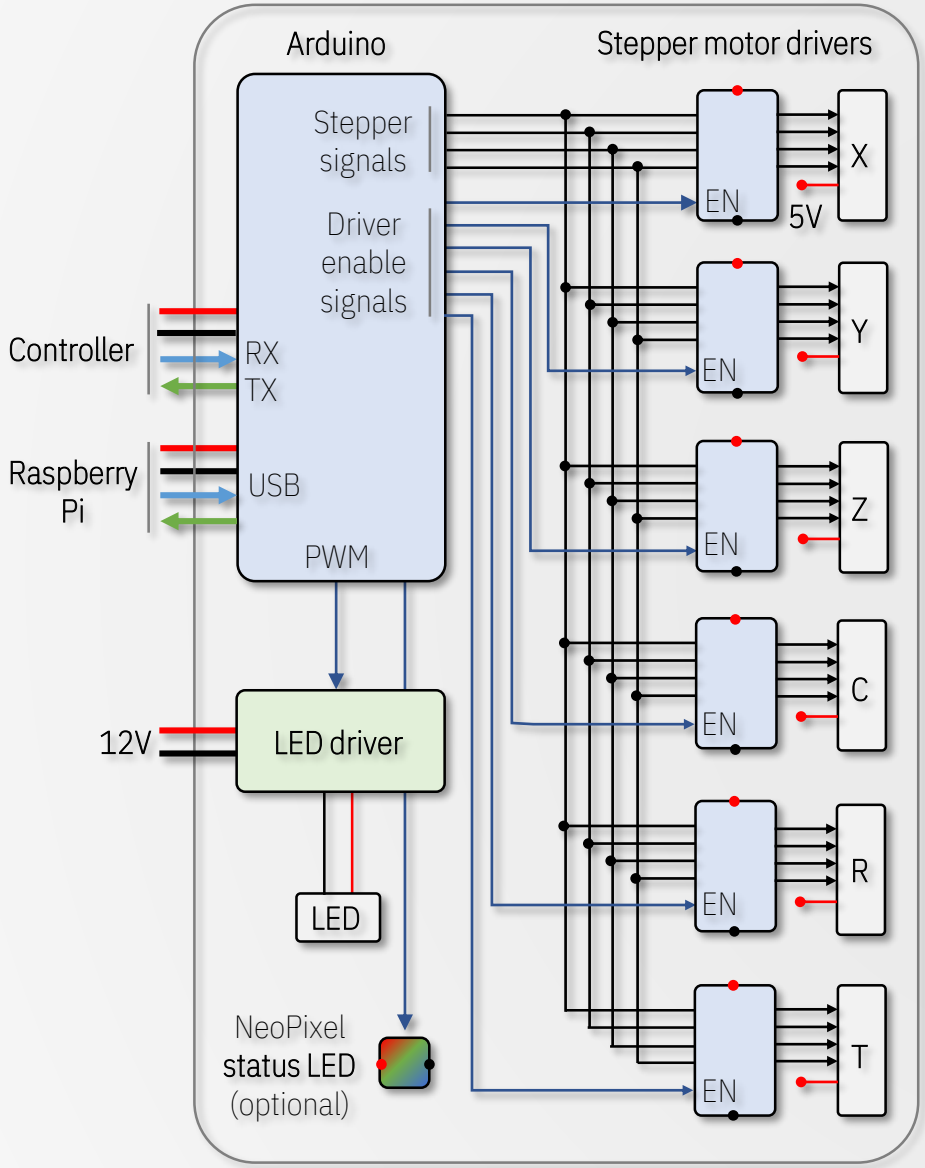
Electronics

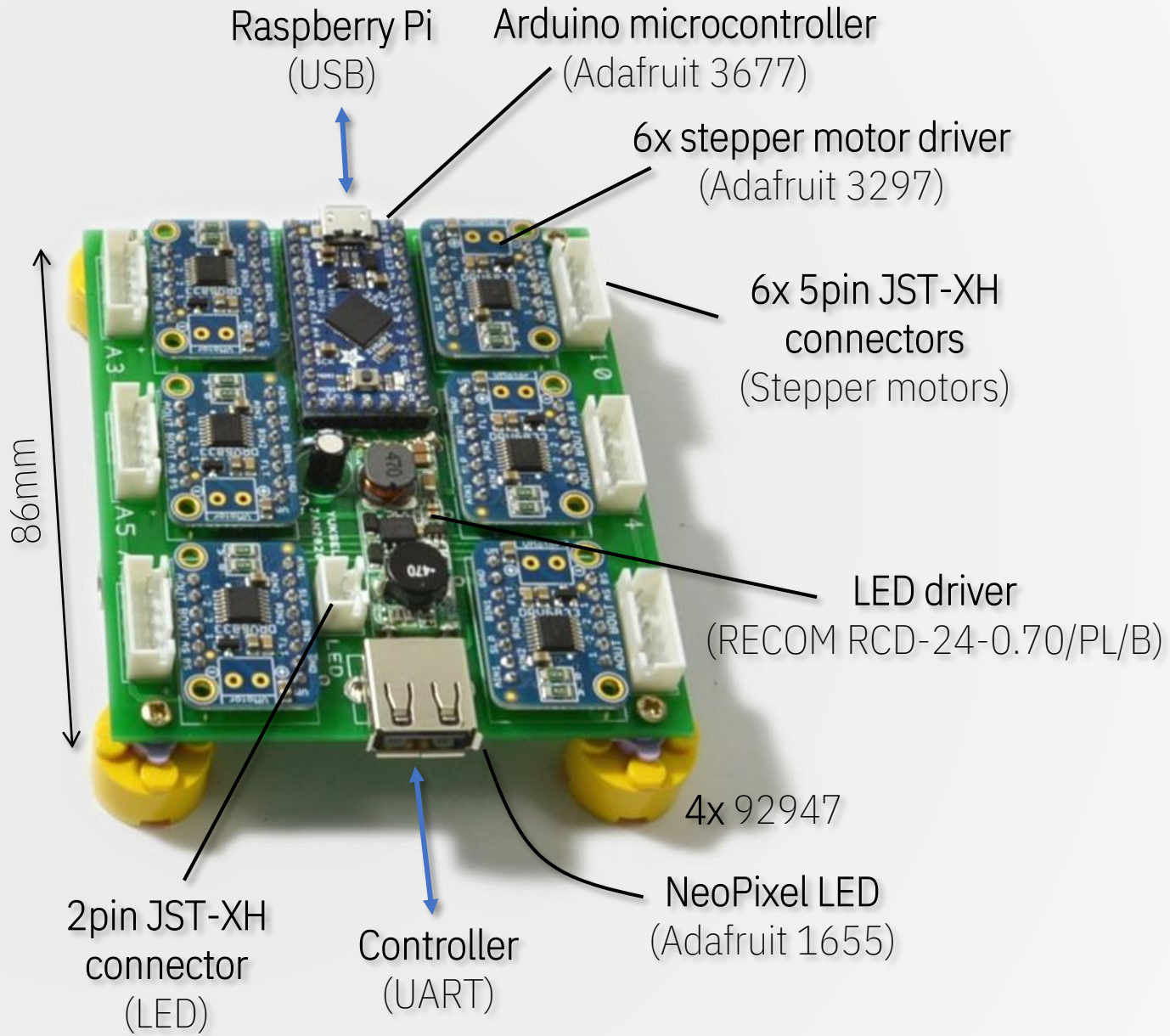


*Note-1: Stepper motors and the illumination LED can be controlled from the **controller (UART)** or the **Raspberry Pi (USB)** or **both***
Note-2: Some high-power LED drivers may require more than 5V, then a DC-DC converter or a separate power supply can be used

Electronics – Mainboard

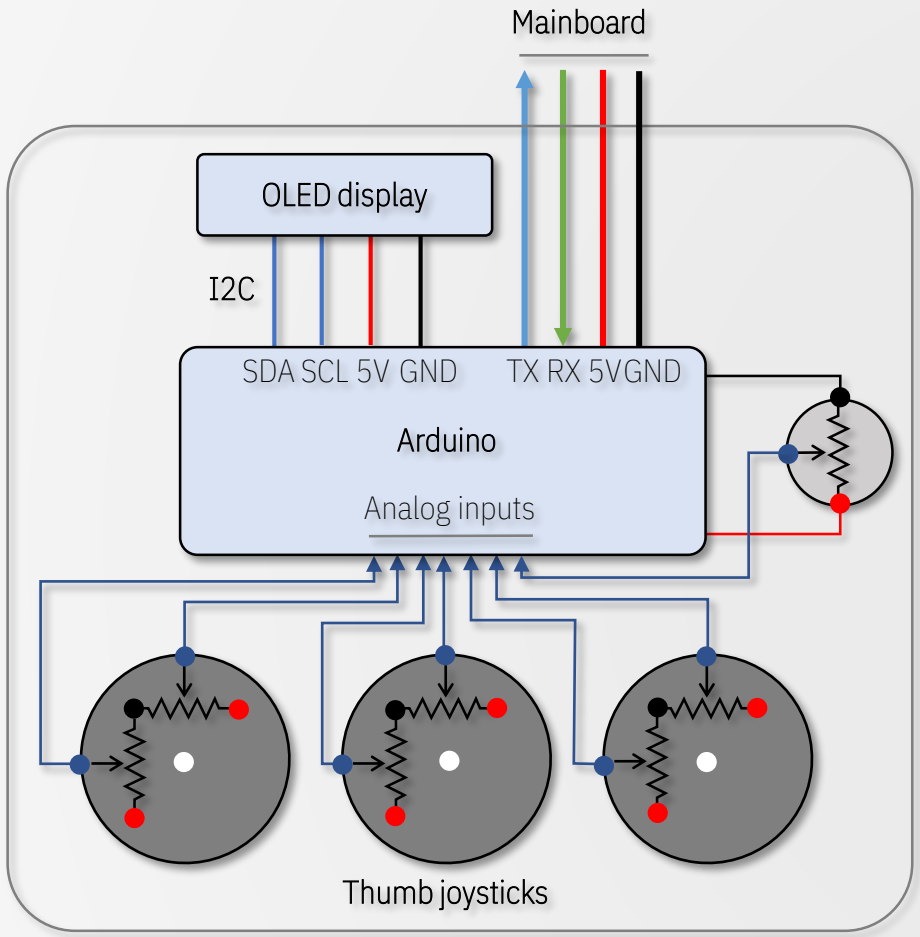
(Photograph)





Electronics – Controller

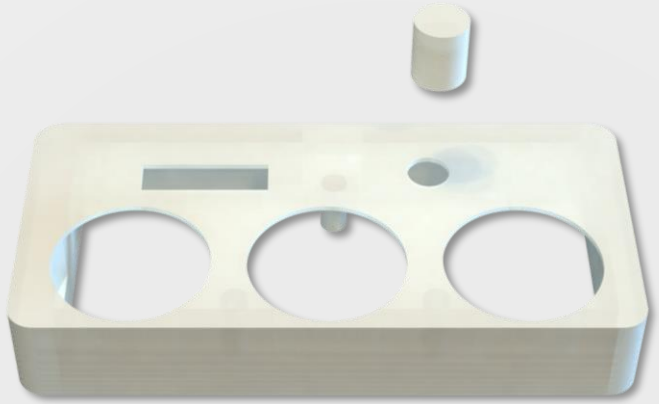
(Photograph)



This joystick controller is fun to use but it is optional, the microscope can also be controlled directly from a keyboard connected to Raspberry Pi using the Python code.

Electronics – Controller

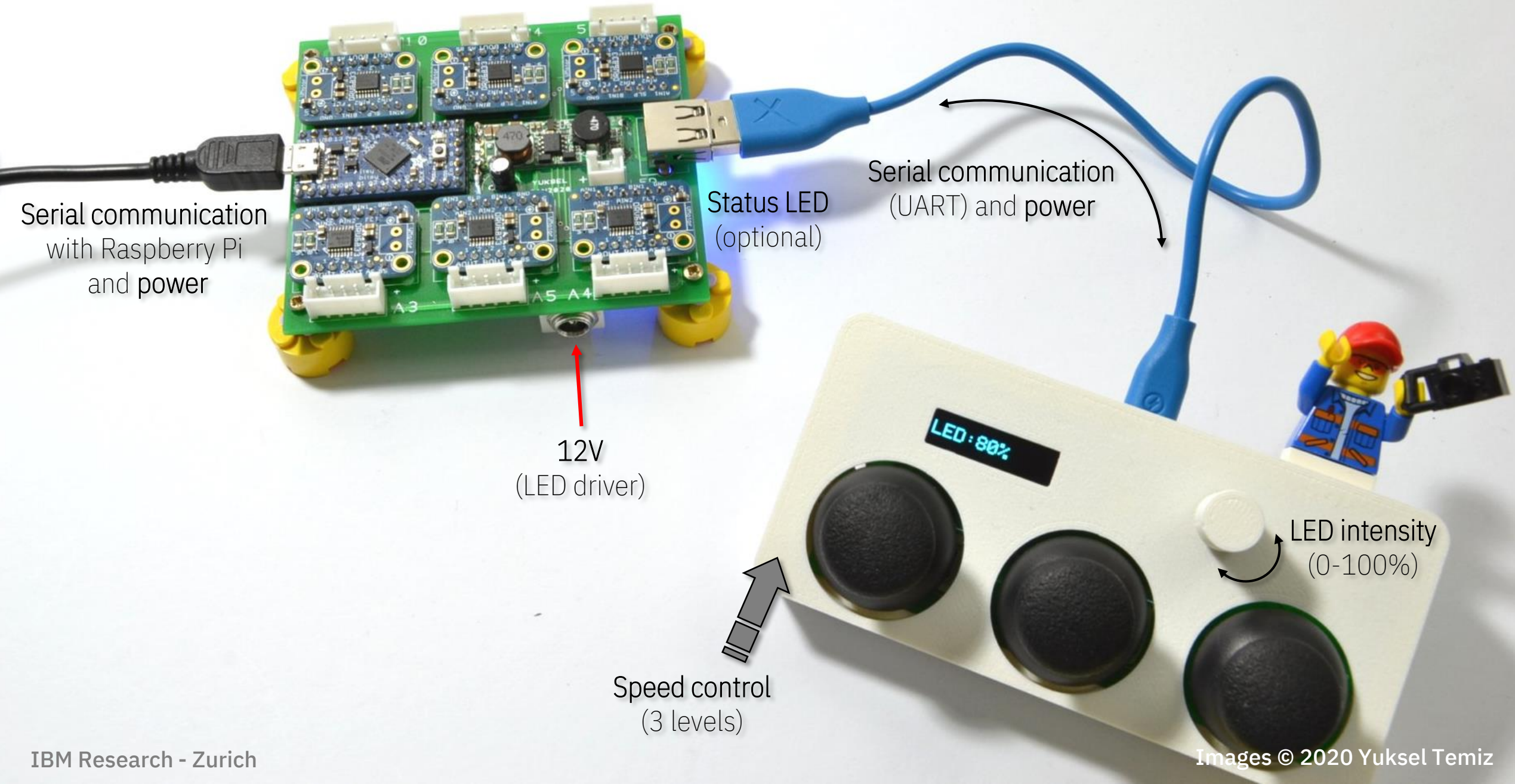
(Photograph)



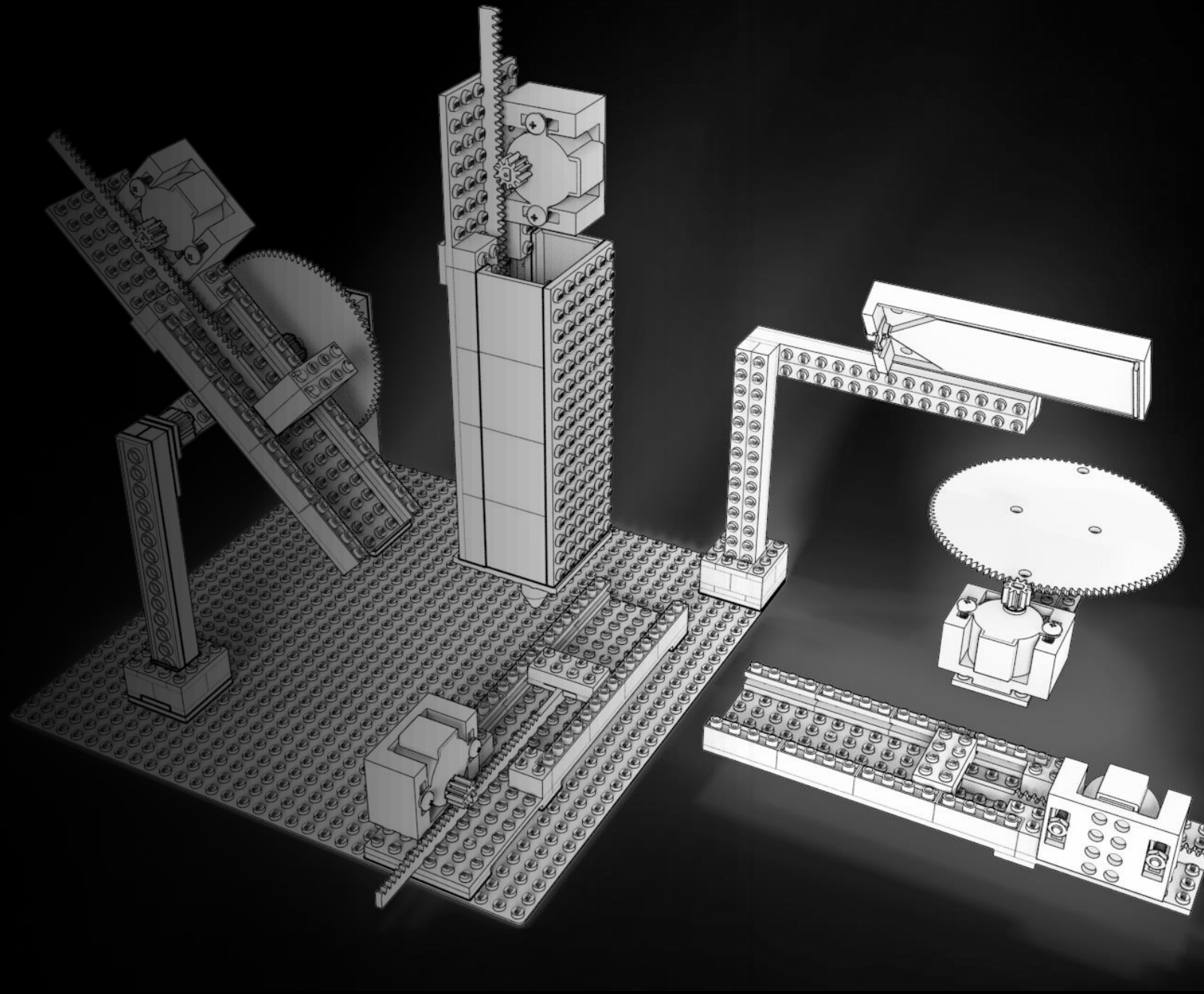
3D printed housing

Electronics – Operation

(Photograph)

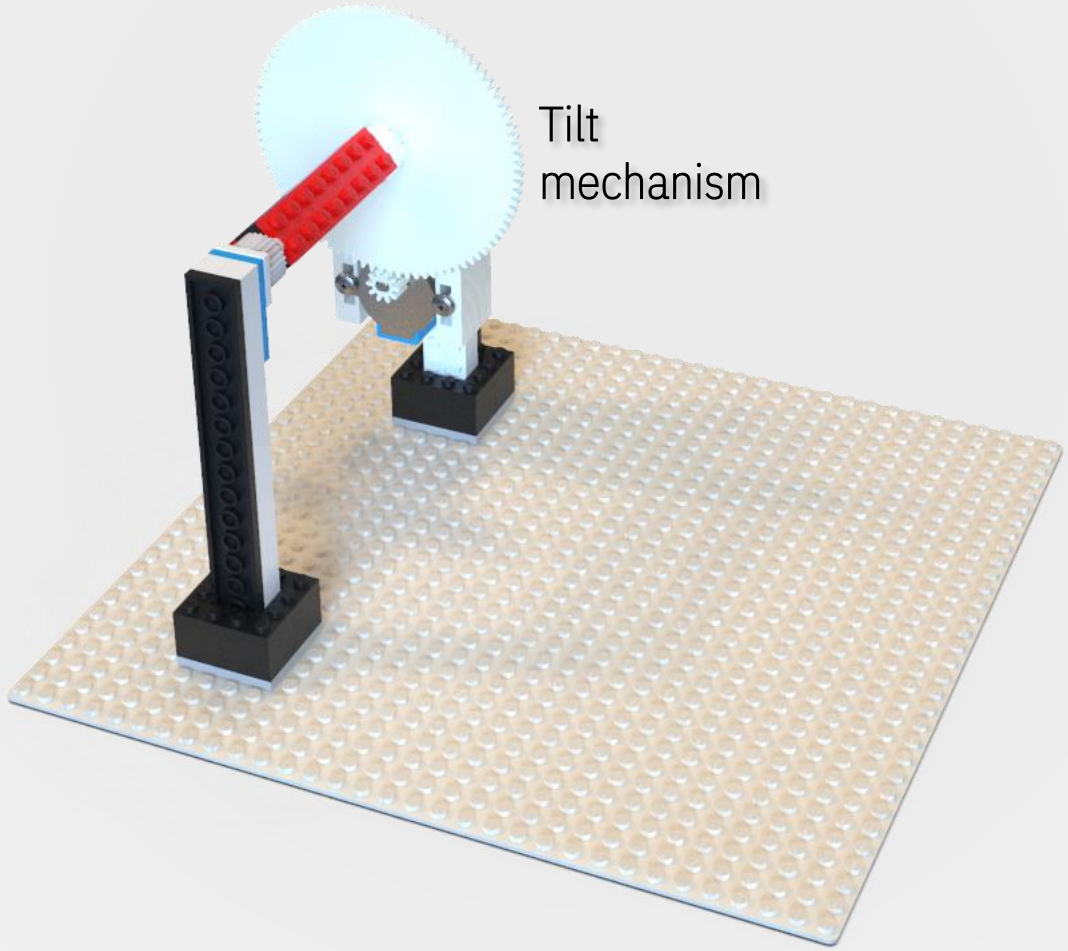


Final assembly

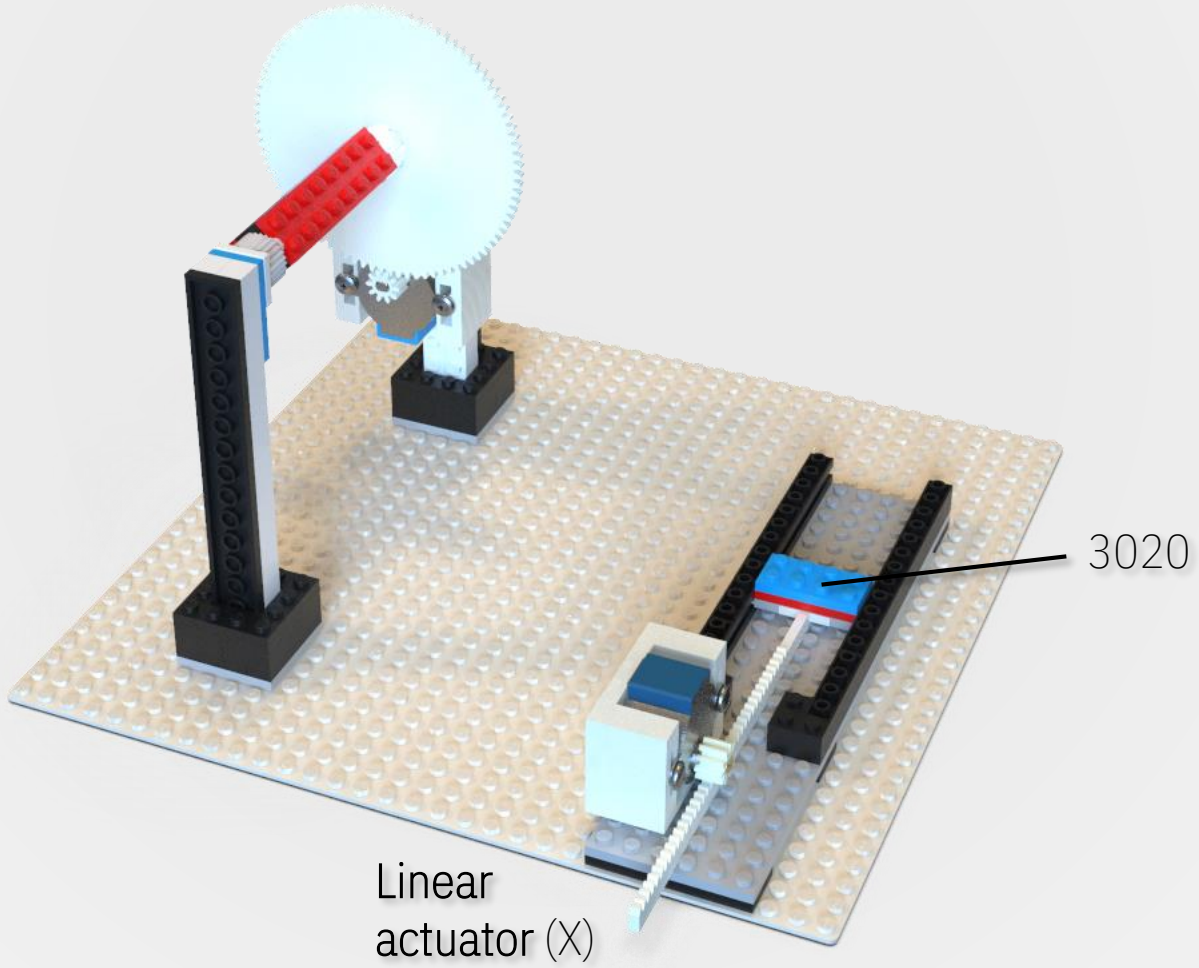


Final assembly

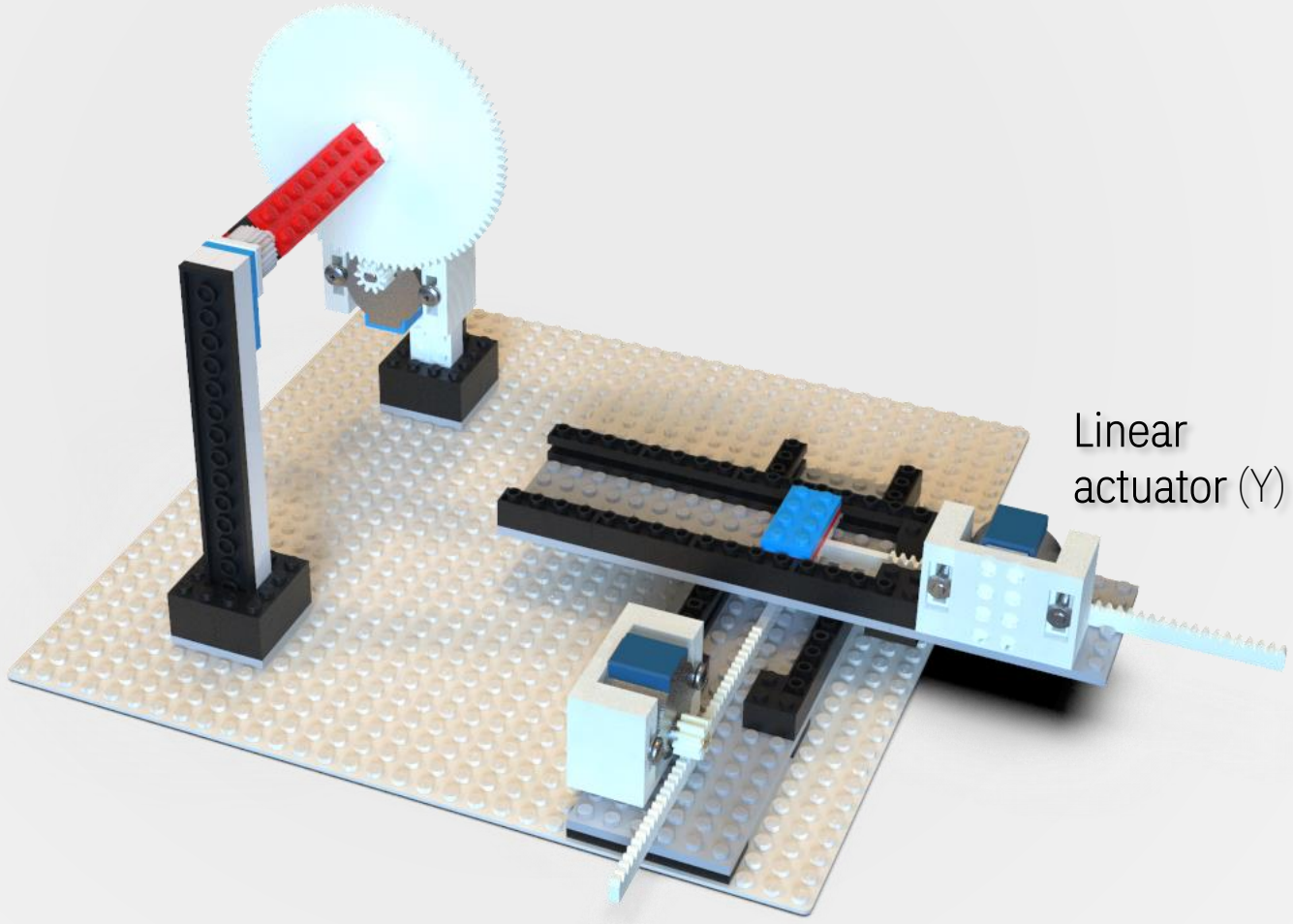
There are several different ways of assembling the microscope. Here is one. Modules can be placed differently depending on the length of the cables, size of the object to be visualized and the microscopy technique.



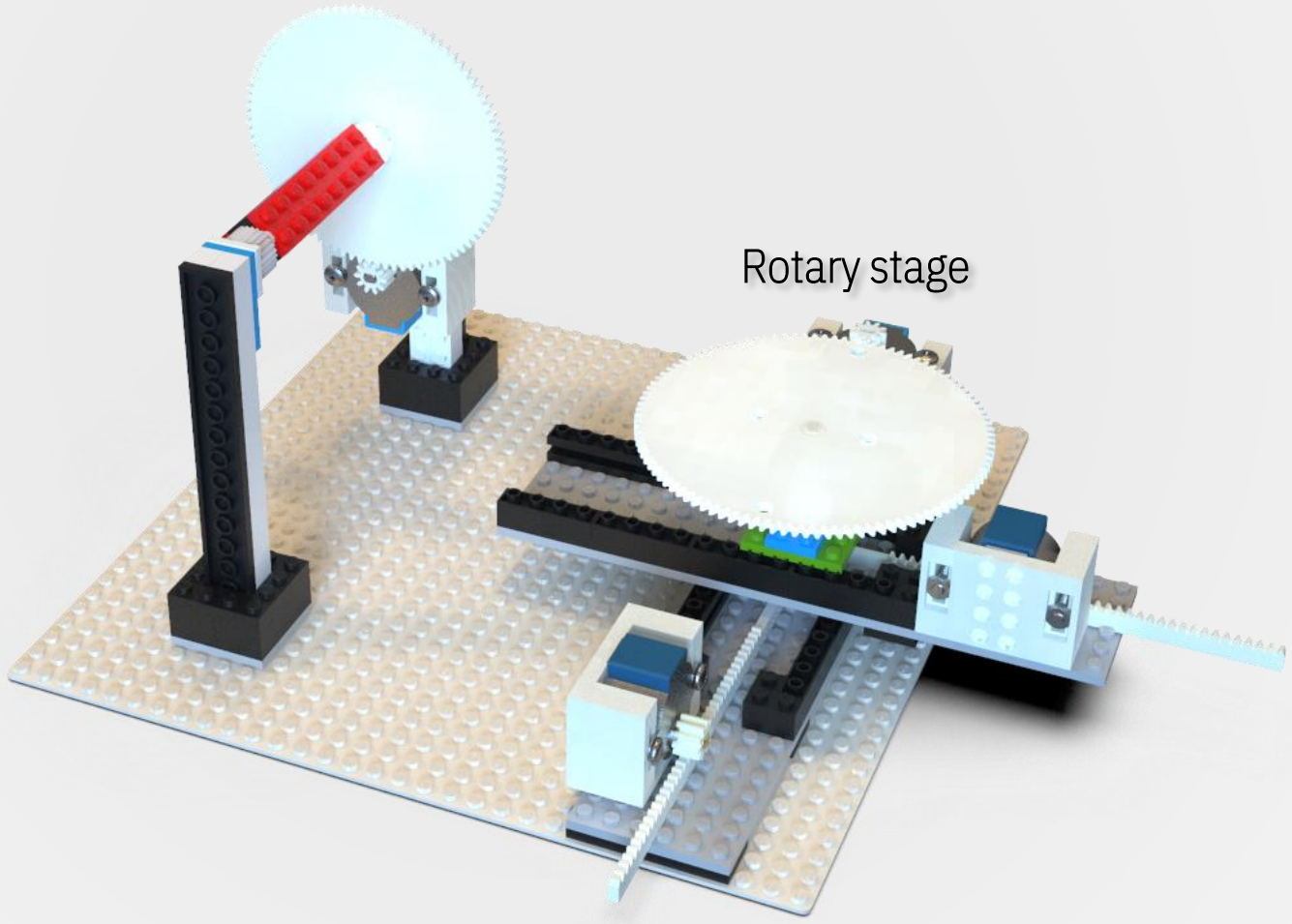
Final assembly



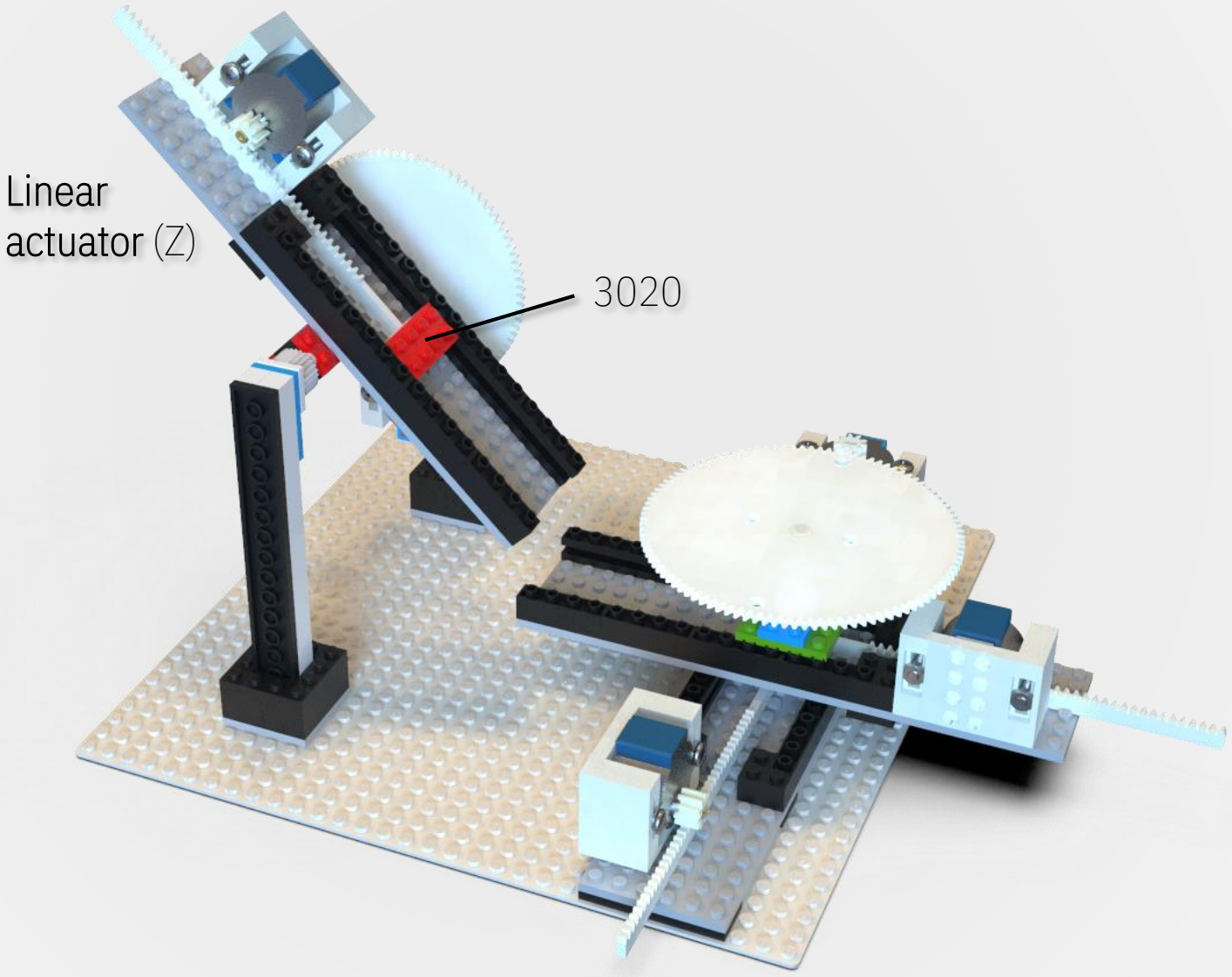
Final assembly



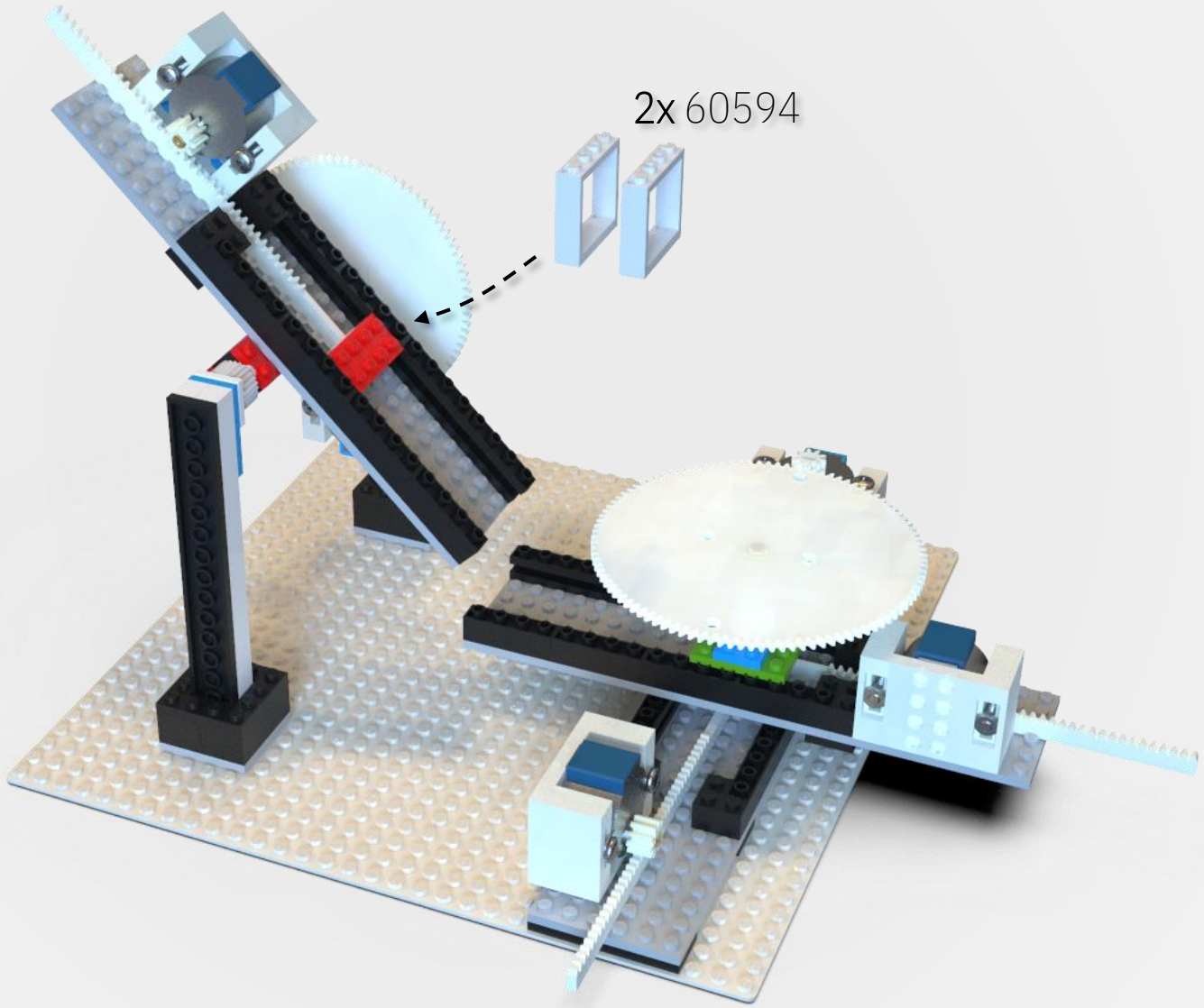
Final assembly



Final assembly



Final assembly



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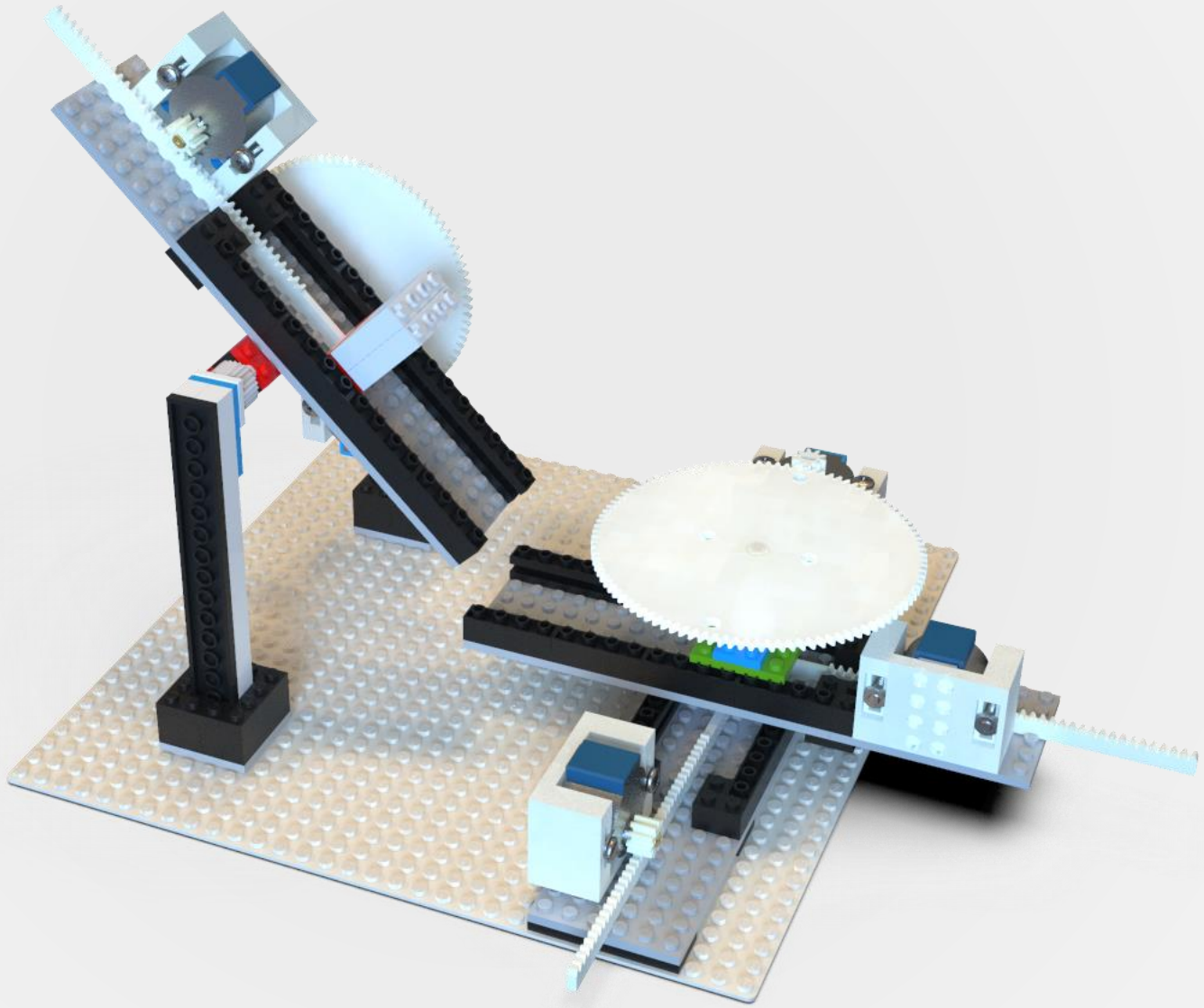

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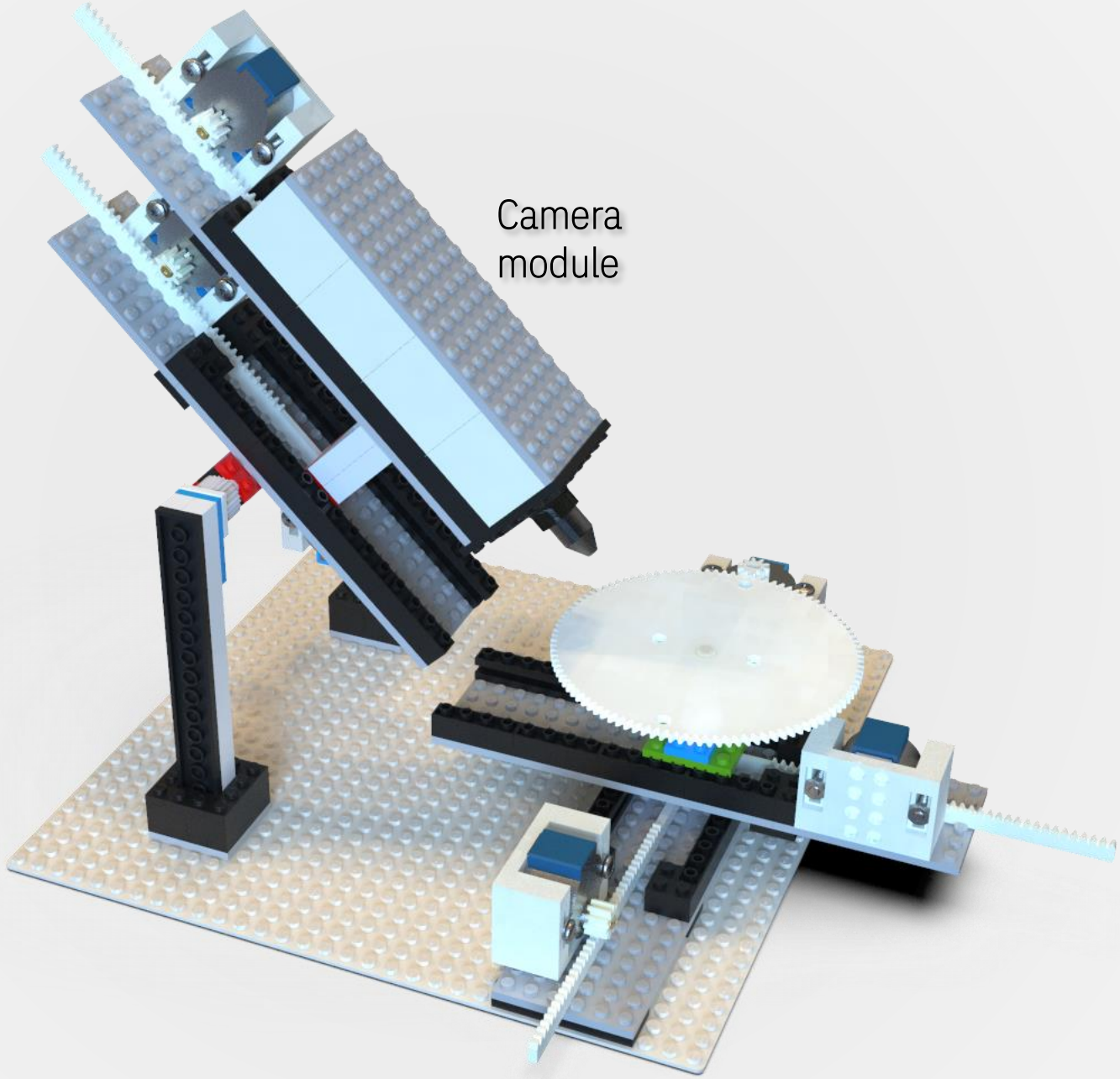
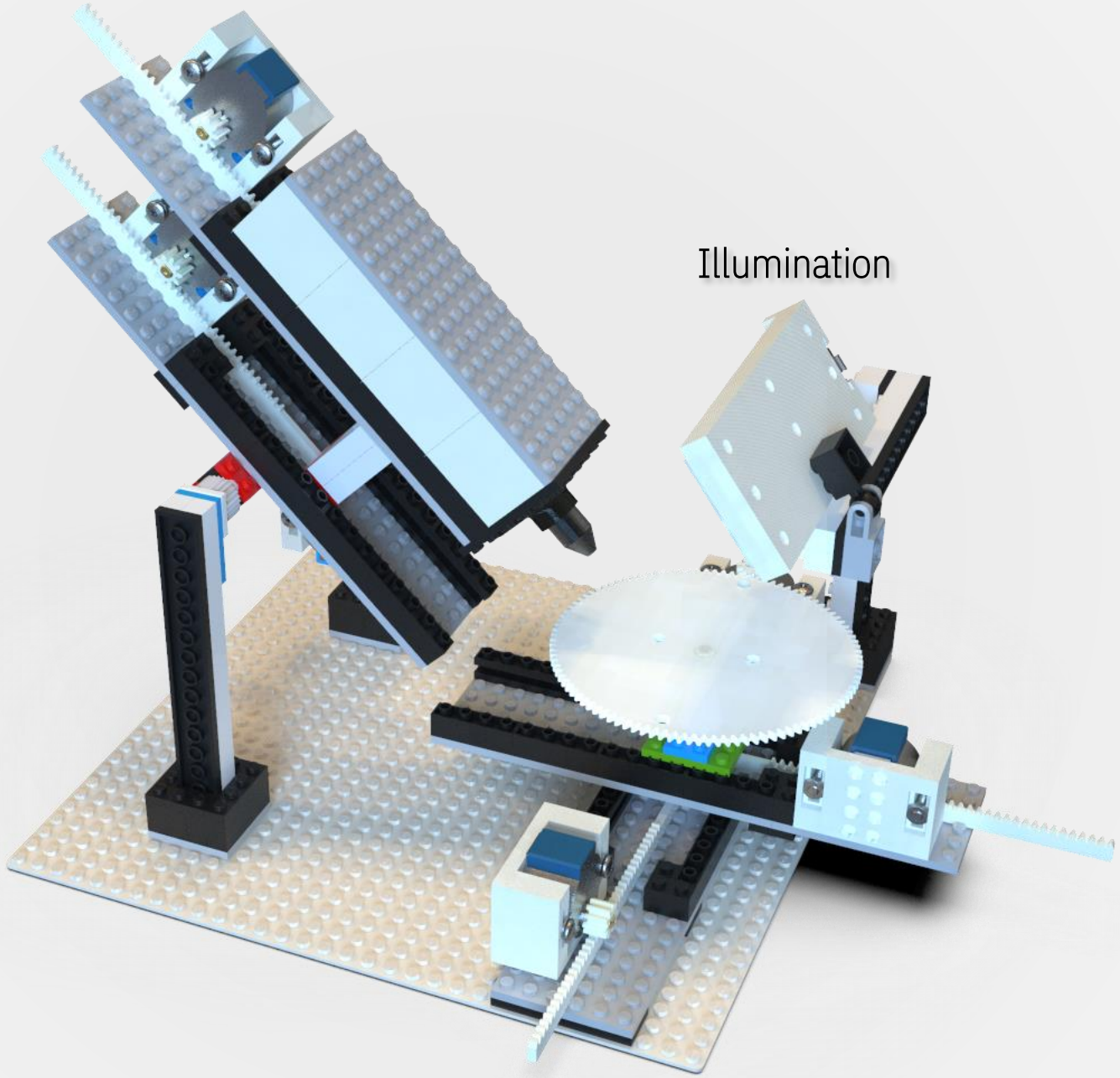
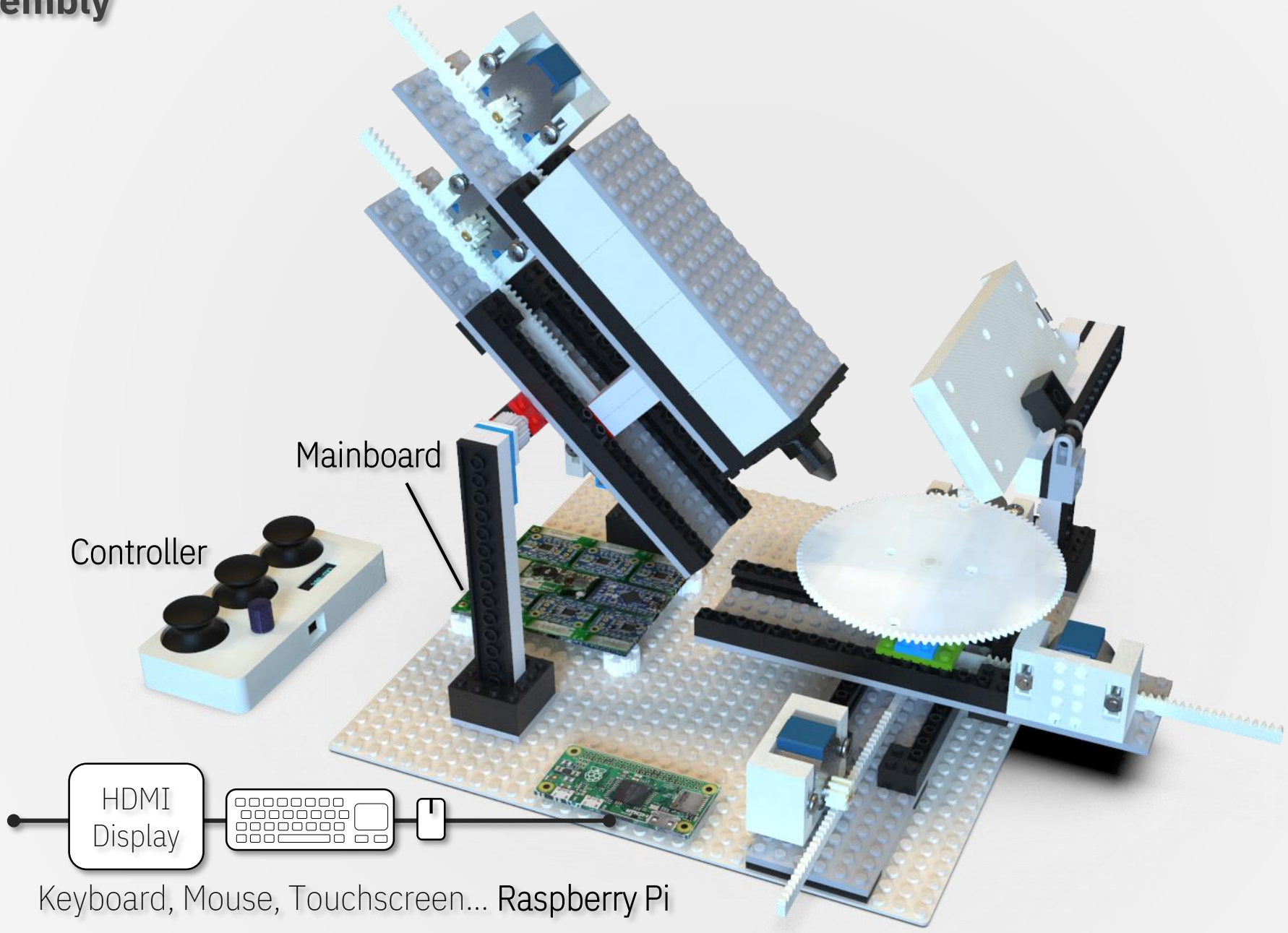


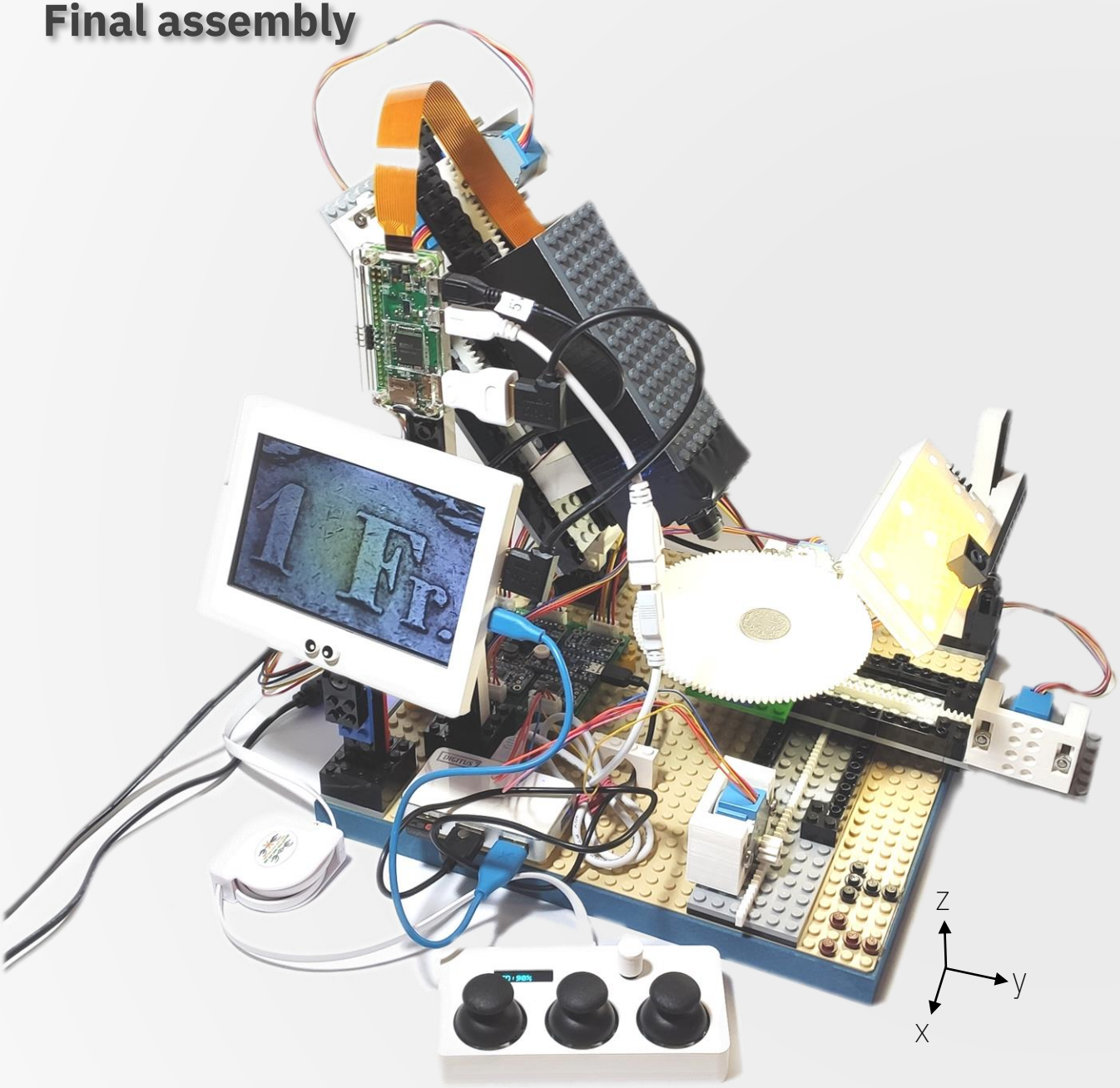
Final assembly

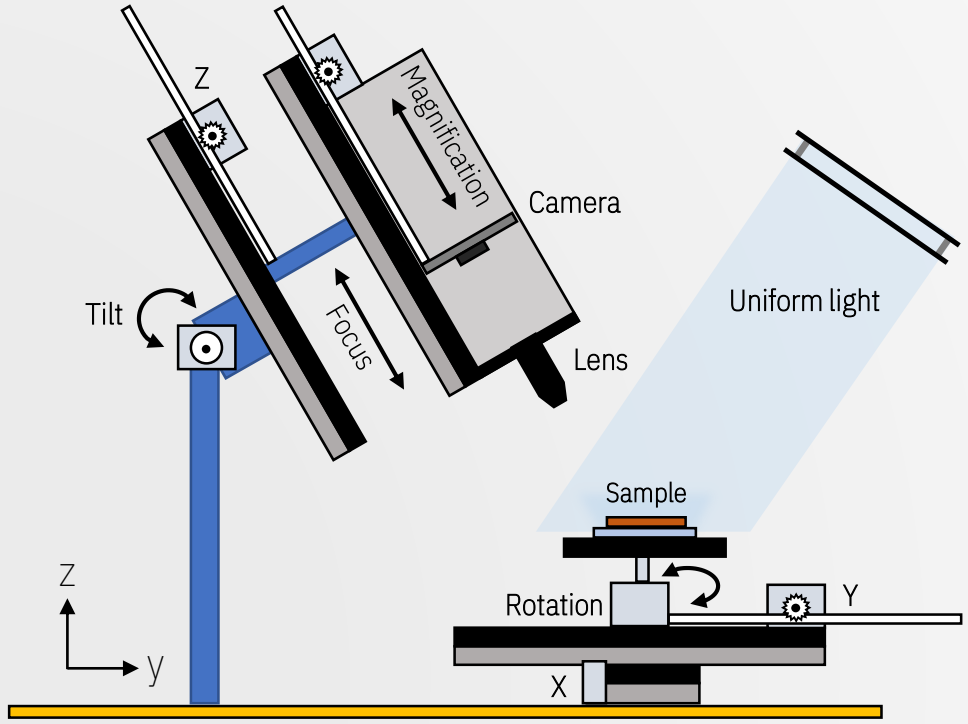


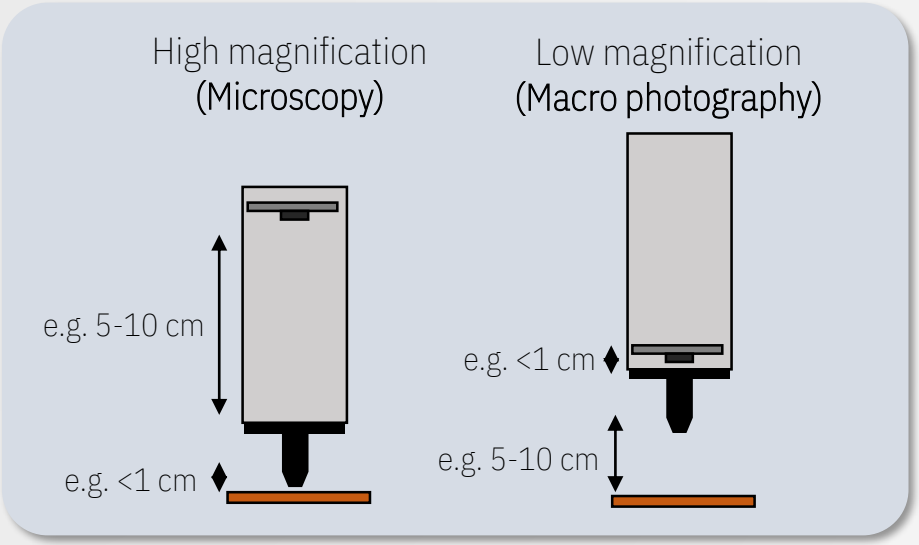
Final assembly



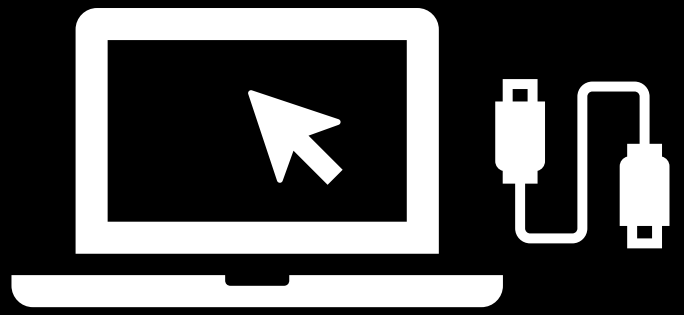
Final assembly







Software

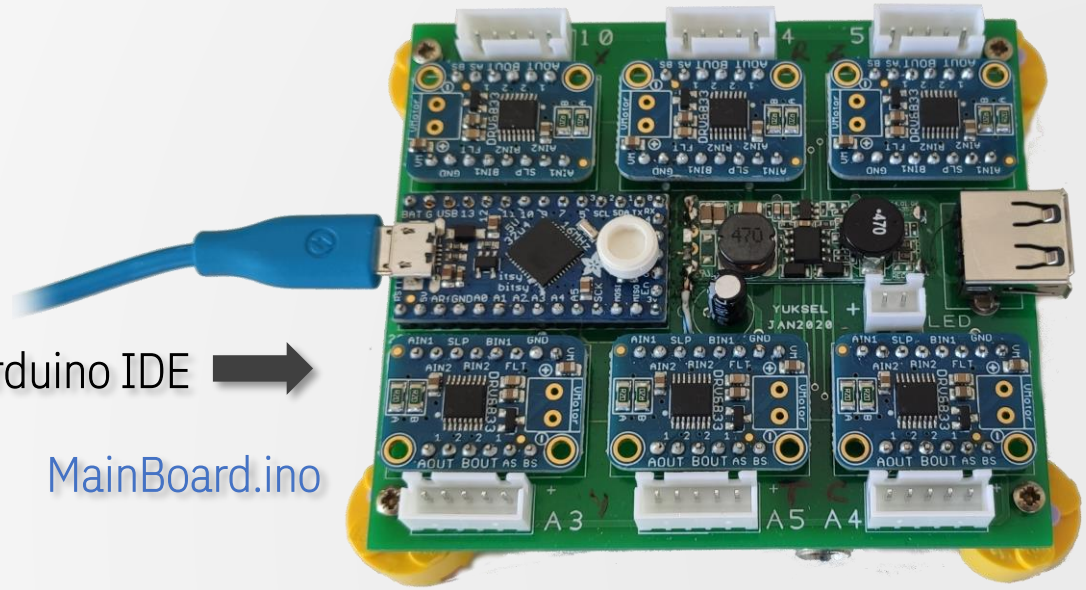


1100100111...

Arduino

(Photograph)

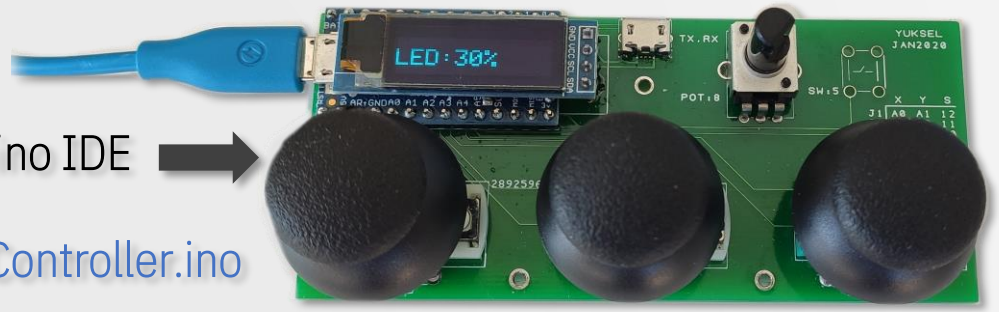
Mainboard



Arduino IDE

MainBoard.ino

Controller



Arduino IDE

Controller.ino

Board: Adafruit ItsyBitsy 32u4 - 5V 16MHz

Required libraries:

- AccelStepper *(for the stepper motors)*
- Adafruit NeoPixel *(for the optional status LED)*

Board: Adafruit ItsyBitsy 32u4 - 5V 16MHz

Required libraries:

- Wire *(for the OLED display)*
- Adafruit_GFX *(for the OLED display)*
- Adafruit_SSD1306 *(for the OLED display)*

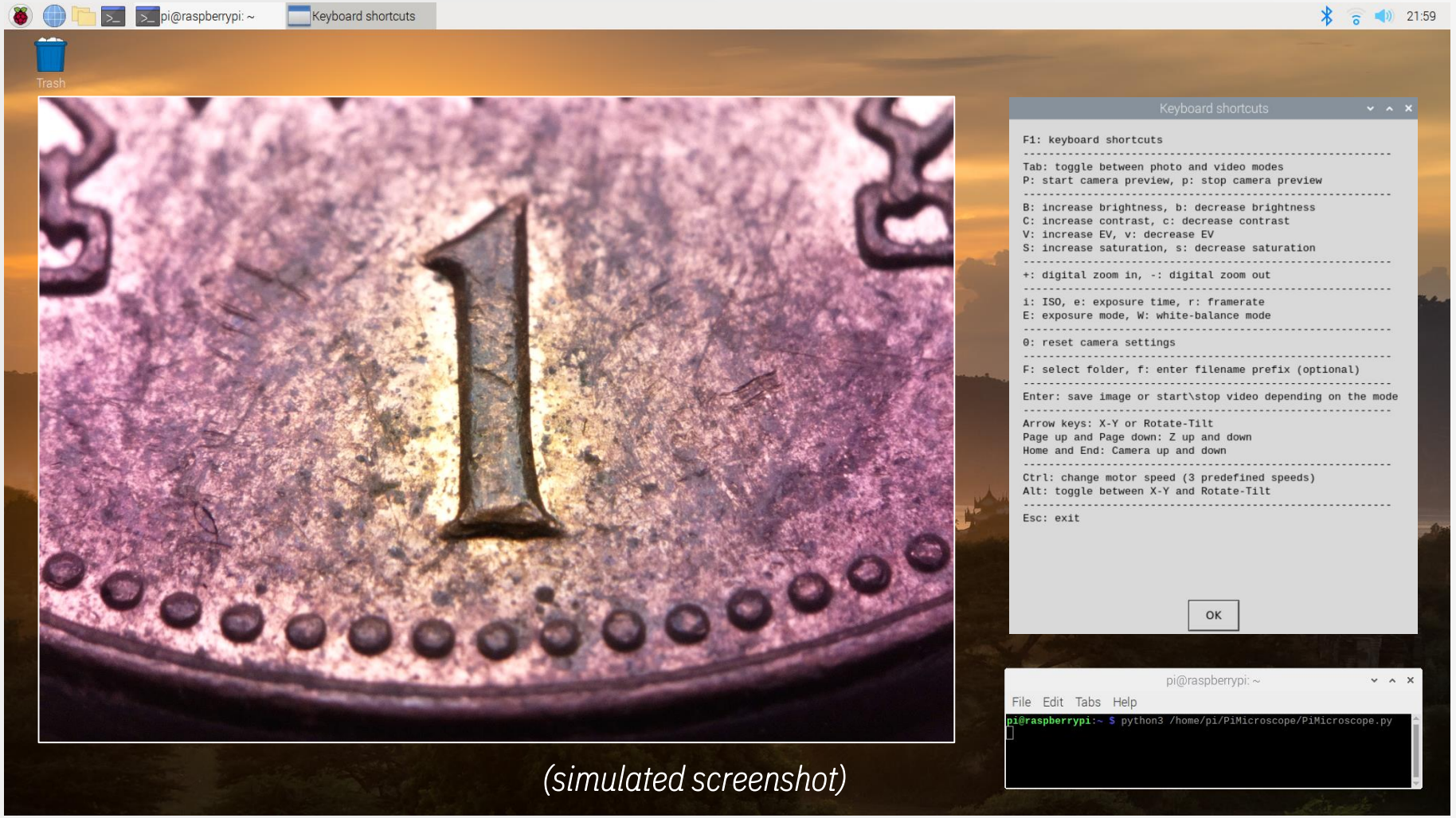
Raspberry Pi – Python

MicroscoPy.py: a program written in Python 3 to control the microscope, modify camera settings and take photos and videos from keyboard

- Sends commands to Arduino mainboard to control the stepper motors and the LED from keyboard (alternative to the joystick controller)

- Modules used:
  - sys
  - easygui
  - pySerial
  - time
  - Pynput

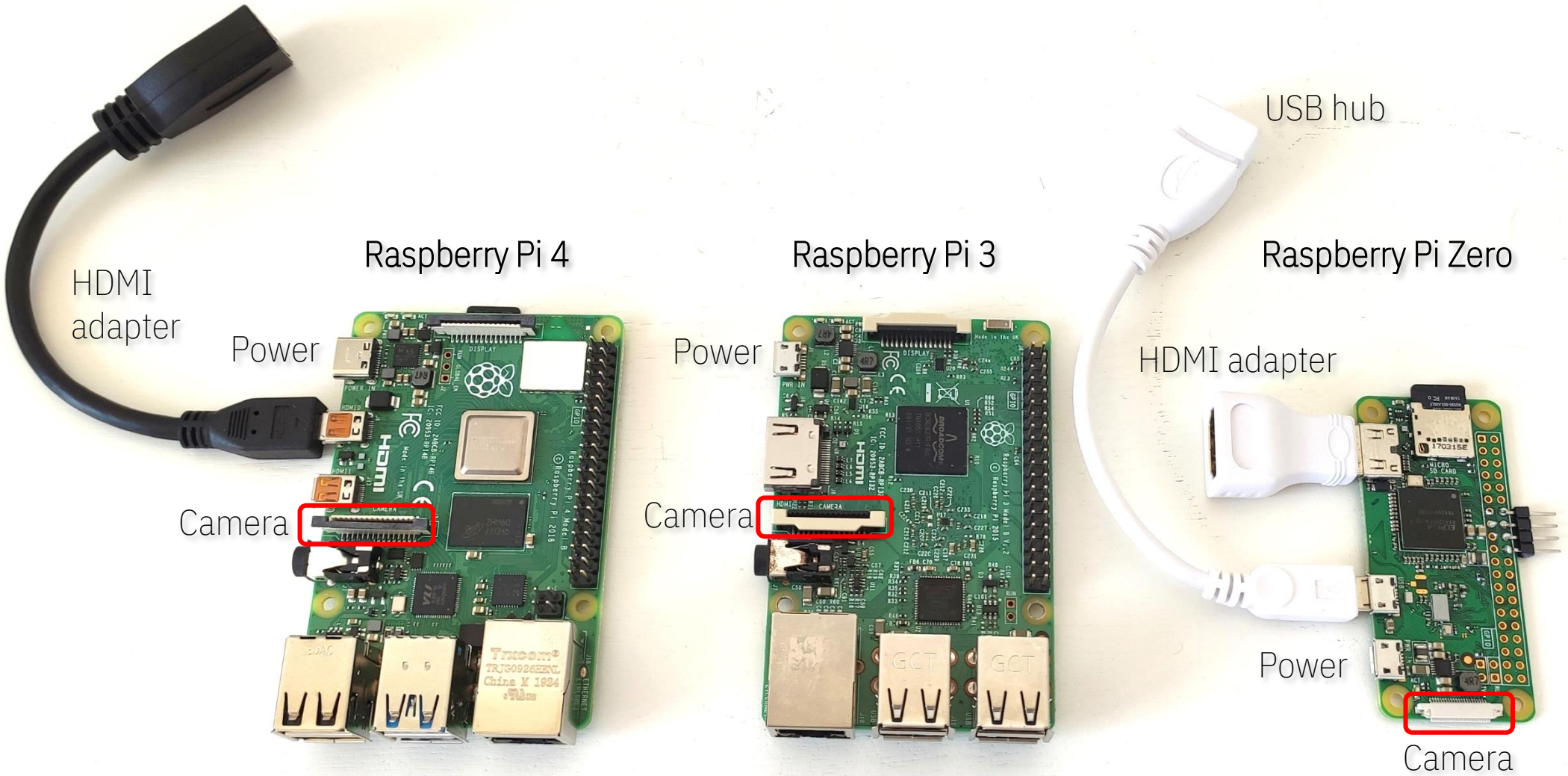
- In Raspberry Pi 4, GPU memory increased to 144MB from 128MB to achieve max. camera resolution



(simulated screenshot)

Raspberry Pi - Python

(Photograph)

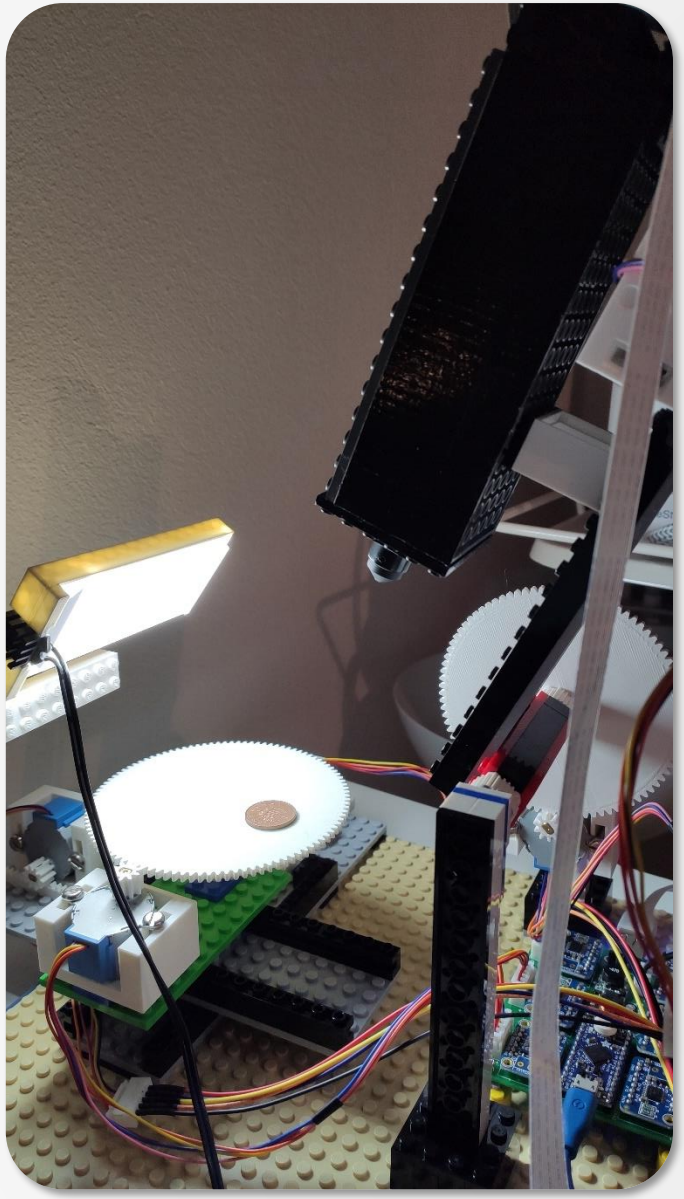


Tested at **3280×2464** (max.) camera resolution

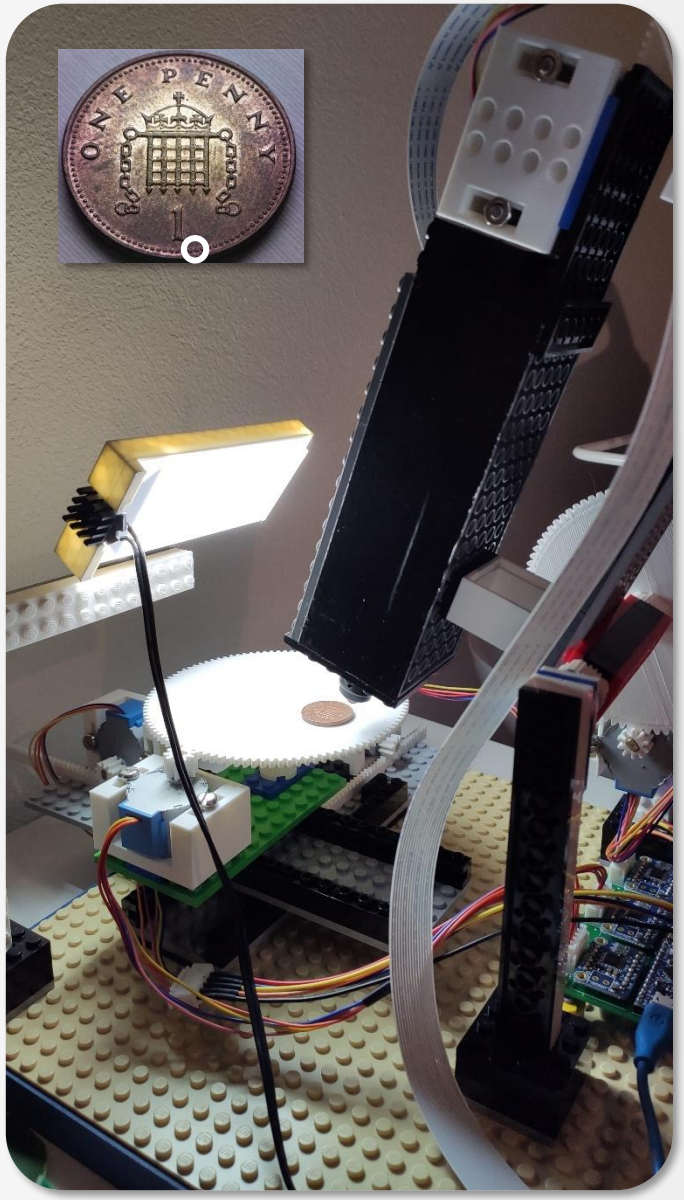
Tested at **1920×1080** camera resolution

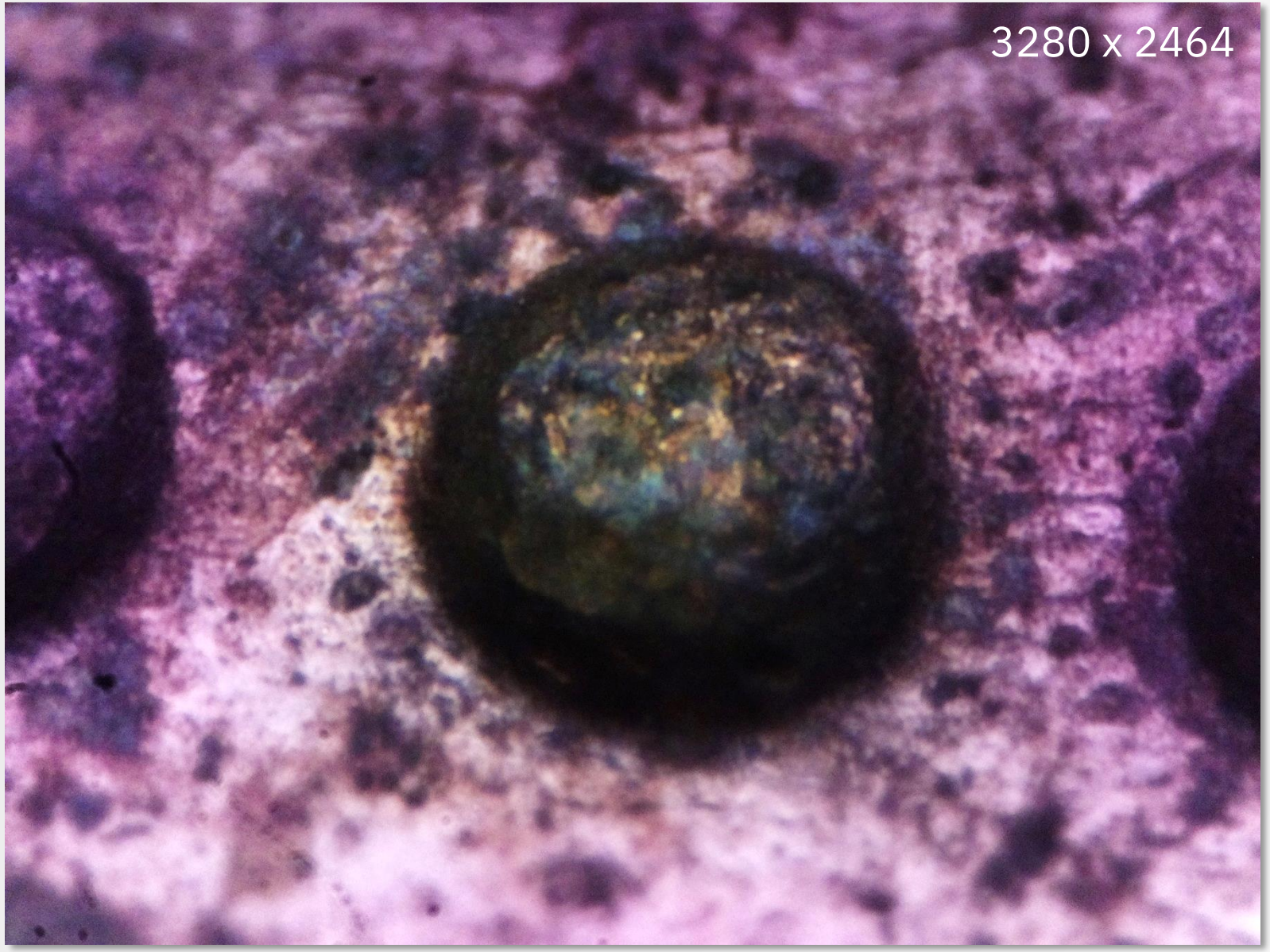
Tested at **1920×1080** camera resolution

Examples of images - macro



Examples of images - micro

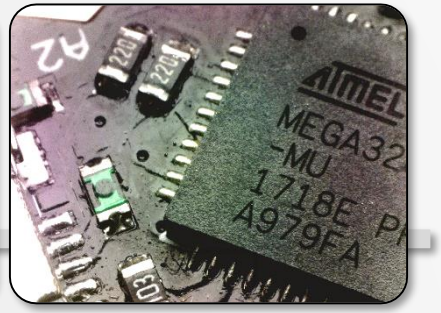


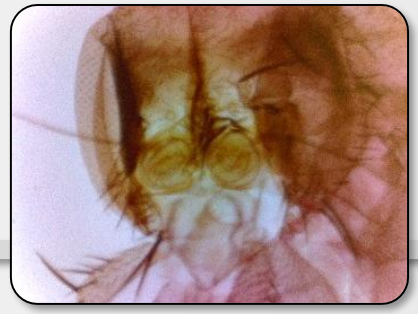


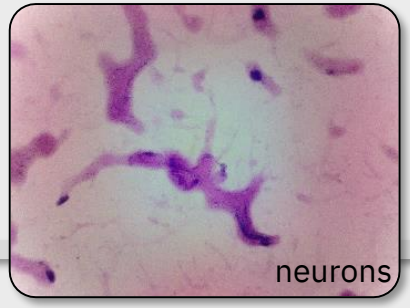
Examples of images

Macro photography and video taken at different angles and magnification



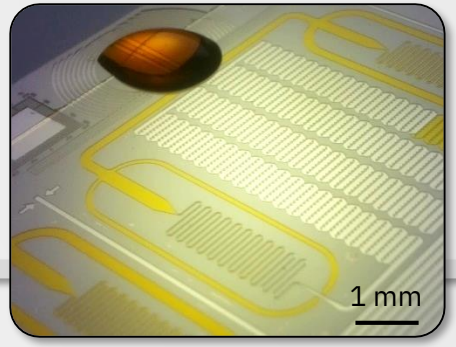


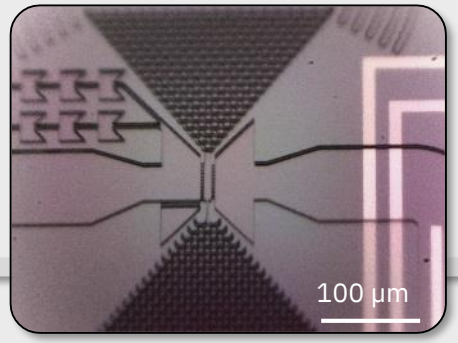


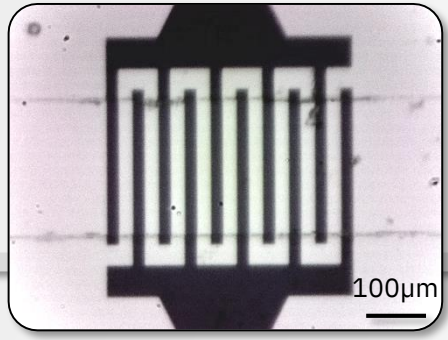



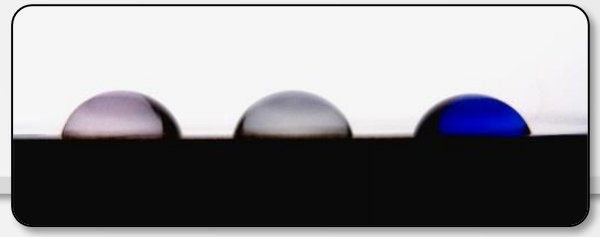
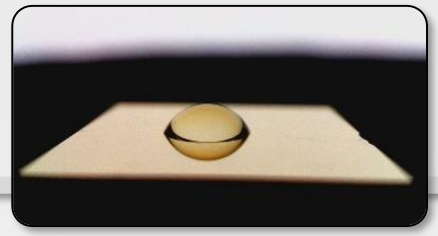
2D and 3D (tilted) imaging of biological samples

Microscopy (reflected or transmitted light)





Contact angle measurements

Bill of materials

Item	Total price ($)	Remarks
LEGO bricks	~60	I recommend buying extra bricks in different sizes.
Raspberry Pi	10-50	Any model works.
Raspberry Pi camera	25	
Camera flex cable	3	A long cable (>40cm) is preferred if the Raspberry Pi cannot be placed closer to the camera.
Magnifying lens	10	M12 thread
Micro SD card	10	Raspberry Pi operating system. Minimum 16GB is recommended.
HDMI display	50-150	Optional if an HDMI display is already available. The price varies depending on the size and the model.
Arduino board x2	20	One for the mainboard, one for the controller. Any Arduino board with enough number of IO pins should work.
Stepper motor driver x6	30	Any other 5V compatible driver should work. Microstepping was not needed in this project.
Stepper motor x6	15	28BYJ-48, 5V, 1/64 gear ratio
JST-XH 5P 4S cables	7	A few of these cables are required the extend the default cable of the stepper motor (28BYJ-48)
High-power LED	4	
High-power LED driver	14	
Light diffuser	3	An LED backlight module is modified by replacing the low-power LED by a high-power one
Potentiometer	1	LED intensity control using pulse-width modulation.
Thumb joysticks x3	12	Three joysticks for X, Y, Z, Camera, Tilt, and Rotation.
5V power supply	20	At least 3A is preferred. A more powerful supply may be needed if the display is also powered from the same supply.
DC-DC converter	3	In case the LED and its driver require more than 5V.
OLED display	3	Displays the LED intensity or any other information on the controller.
USB connector (type A)	0.5	Connection between the mainboard and the controller (mainboard side).
USB connector (micro)	0.5	Connection between the mainboard and the controller (controller side).
JST XH connector set	5	Connectors for the stepper motors and the LED
DC barrel connector	1	In case a separate DC input (e.g. 12V) is needed for the LED
OVERALL TOTAL	~300	

- The prices and the links are for exemplary components that were used in this prototype.
- Any other compatible model should work in principle.
- The total price varies significantly depending on the vendor and the model. For example, the type of the Raspberry Pi and the display makes a big difference in the price.
- The cost of 3D-printed parts is not included.
- There are also a few other accessories needed, like USB cables, an HDMI cable, optionally a mouse and a keyboard, an ON/OFF switch, screws and nuts, and printed circuit boards (PCBs).

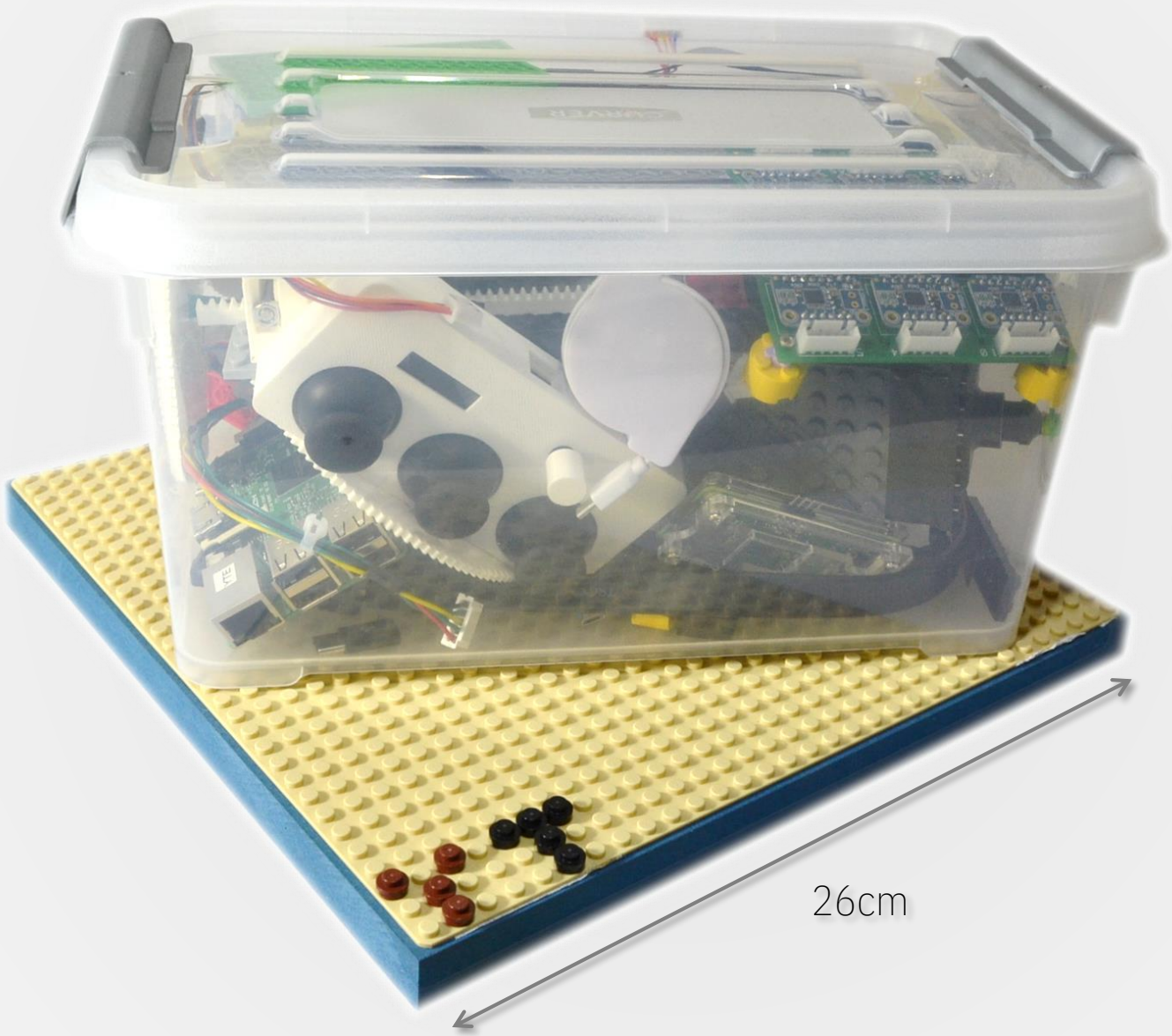
List of 3D-printed parts

Click on the design name to go to the corresponding page

Design name	Function/module	Units needed	Slicer settings – printing speed	Remarks
1-RackGear.stl	Linear stages	4	Super quality (0.12mm) – 20mm/s	Requires support structures. Sides of the rack may require minor polishing
2-MotorGear.stl	All stepper motors	6	Super quality (0.12mm) – 20mm/s	
3-MotorHousing.stl	All stepper motors	6	Low quality (0.28mm) – 50mm/s	
4-CameraAdapter.stl	Camera	1	Standard quality (0.2mm) – 50mm/s	
5-LensAdapter.stl	Camera	1	Standard quality (0.2mm) – 50mm/s	Not needed if a commercial lens holder is used
6-ShaftAdapter.stl	Rotary stage – option1	1	Super quality (0.12mm) – 20mm/s	Not needed if the more precise stage (option 2) is used
7-RotationGear.stl	Rotary stage – option2	1	Standard quality (0.2mm) – 50mm/s	Not needed if the less precise stage (option 1) is used
8-TiltGear.stl	Tilting mechanism	1	Standard quality (0.2mm) – 50mm/s	
9-LEDhousing.stl	Illumination	1	Low quality (0.28mm) – 50mm/s	
10-LEDfixture.stl	Illumination	1	Low quality (0.28mm) – 50mm/s	A small piece to keep everything in place

- Parts were designed using **FreeCAD** (www.freecadweb.org/), sliced using **Ultimaker Cura** (ultimaker.com/software/ultimaker-cura), and printed using **Creality Ender 3 Pro** printer with a metal extruder and a BLTouch auto bed-leveling sensor.
- 1.75mm white **PLA filament** (Purefil, Switzerland) was used (extruder Temperature: 200 °C, bed temperature: 60 °C).
- A good quality printing depends on many factors and parameters, especially a good bed leveling.
- Some parts, especially the holes fitting to the studs of LEGO bricks, may require soft grinding using a file or a sandpaper.
- Gears used in the illustrations and the first prototype had a larger pitch. The latest design files have a finer pitch for better precision. All designs have been tested.

Storage



- LEGO bricks
- 3D printed parts
- Raspberry Pi + camera
- Arduino mainboard
- Arduino controller
- HDMI display
- Cables …

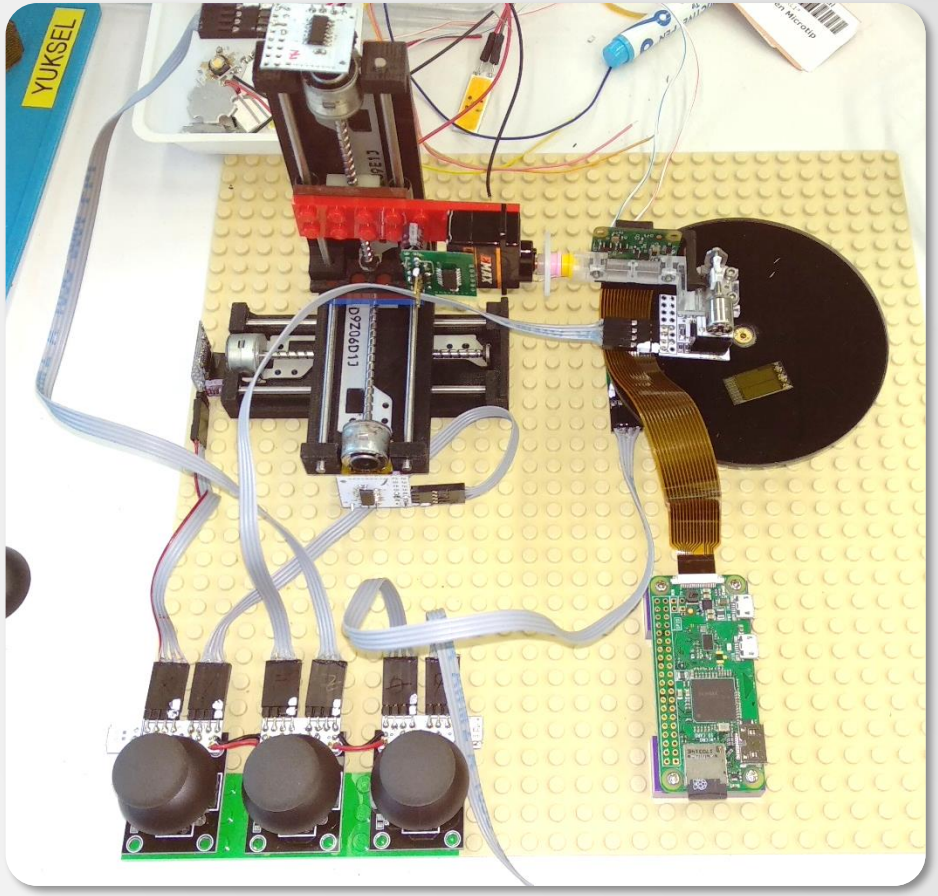
Learning by failing

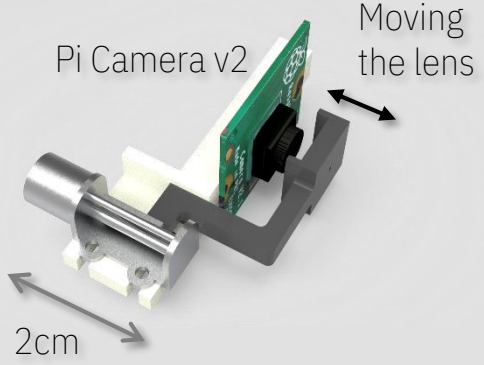
“Experience is a truer guide than the words of others”

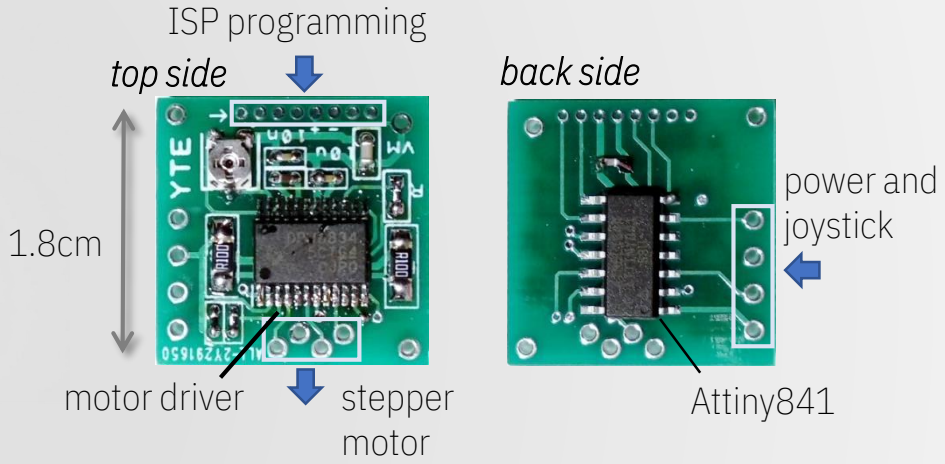
Leonardo da Vinci

Learning by failing – 1 (stepper motors from CD-ROMs)

- XYZ stage: 3D printed linear actuators using stepper motors from CD-ROMs
- Camera focus/magnification: Moving the camera lens using a tiny stepper motor
- Electronics: Custom Arduino board using Attiny841 microcontroller (one board for each motor)
- Mechanical parts: Mostly 3D printed, only a few LEGO bricks





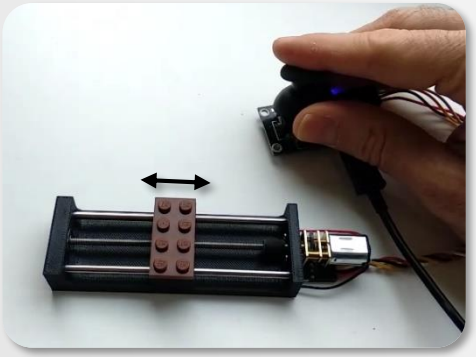


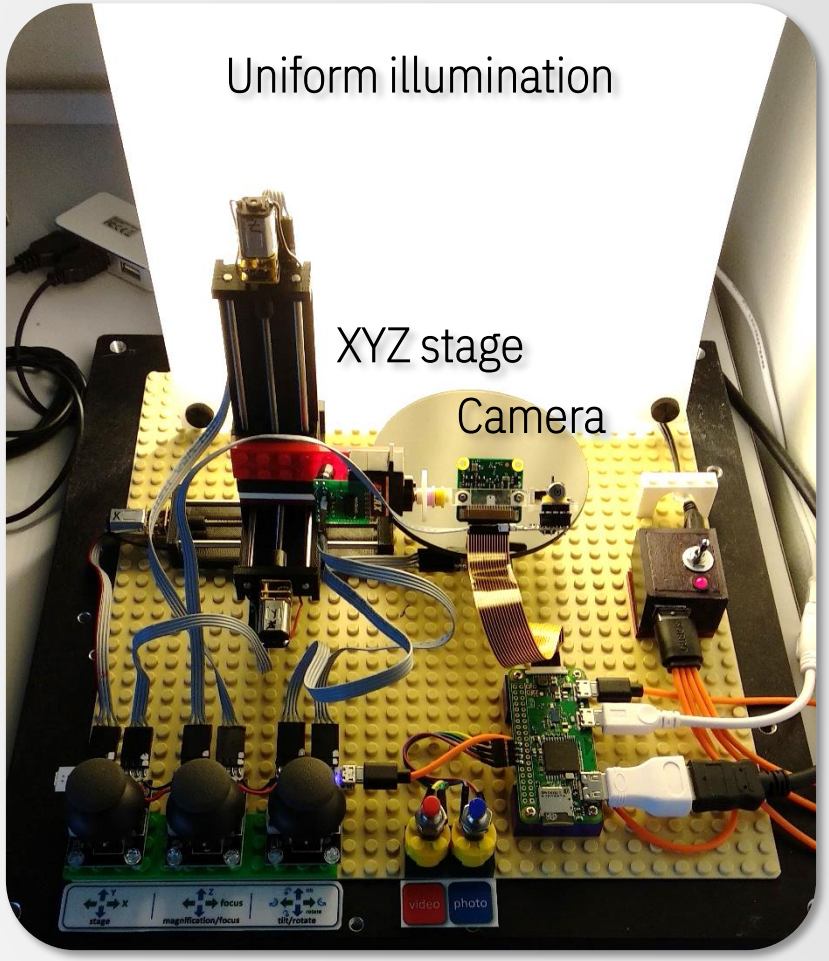
Issues:

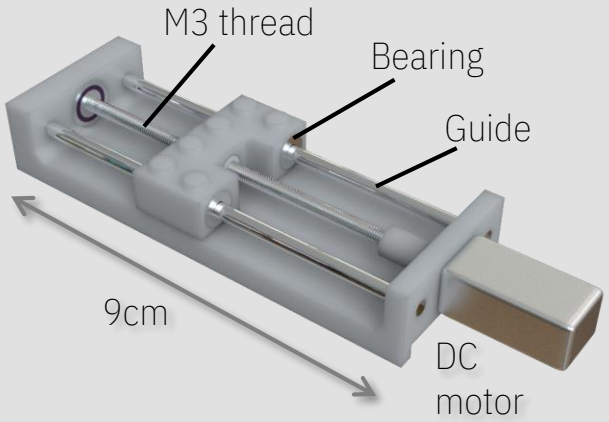
- Custom-design components, not available off-the-shelf
- Limited travel distance and magnification range
- Linear movements not very smooth (18-degree per step)
- Difficult to protect the image sensor from stray light
- Assembly of the custom Arduino/motor driver board requires high precision soldering

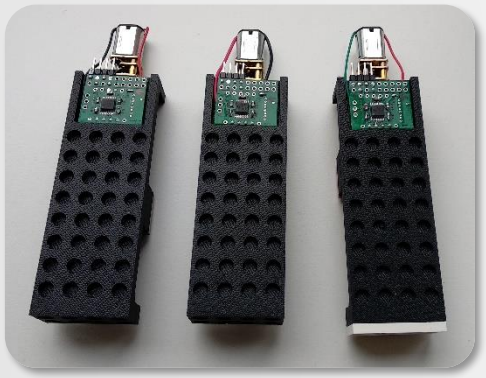
Learning by failing – 2 (DC gear motors)

- XYZ stage: 3D printed linear actuators using DC gear motors
- Camera focus/magnification: Moving the camera lens using a tiny stepper motor
- Electronics: Custom Arduino board using Attiny841 microcontroller (one board for each motor)
- Mechanical parts: Mostly 3D printed, only a few LEGO bricks







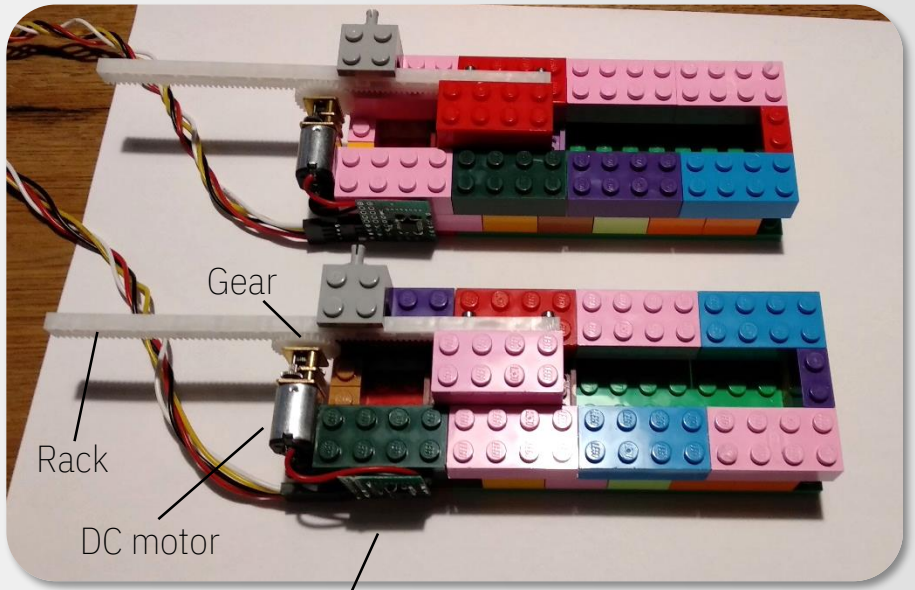


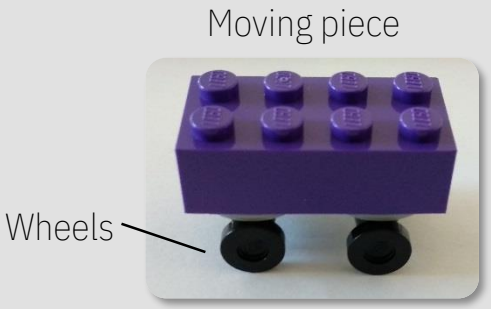
Issues:

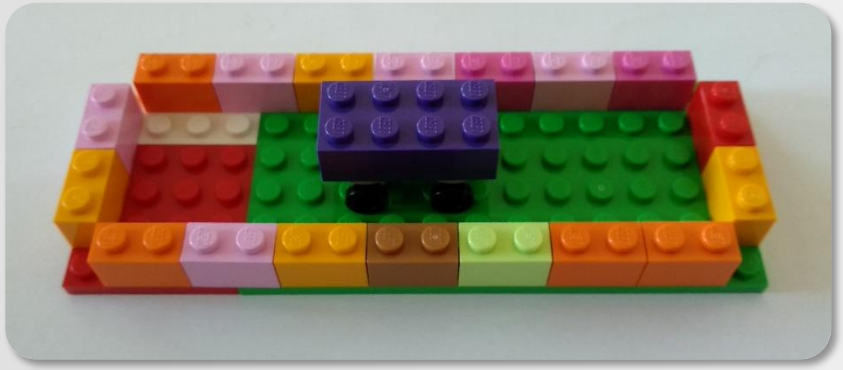
- Custom-design components, not available off-the-shelf
- Smoother movements but cannot take much load at lower speeds
- Thread and guides bend when pushed too much, resulting in wobbles during movement

Learning by failing – 3 (DC motor + pinion gear + rack)

- XYZ stage: Moving a LEGO piece using a gear + rack combination
- Camera focus/magnification: Moving the camera lens using a tiny stepper motor
- Electronics: Custom Arduino board using Attiny841 microcontroller (one board for each motor)
- Mechanical parts: Mostly LEGO bricks



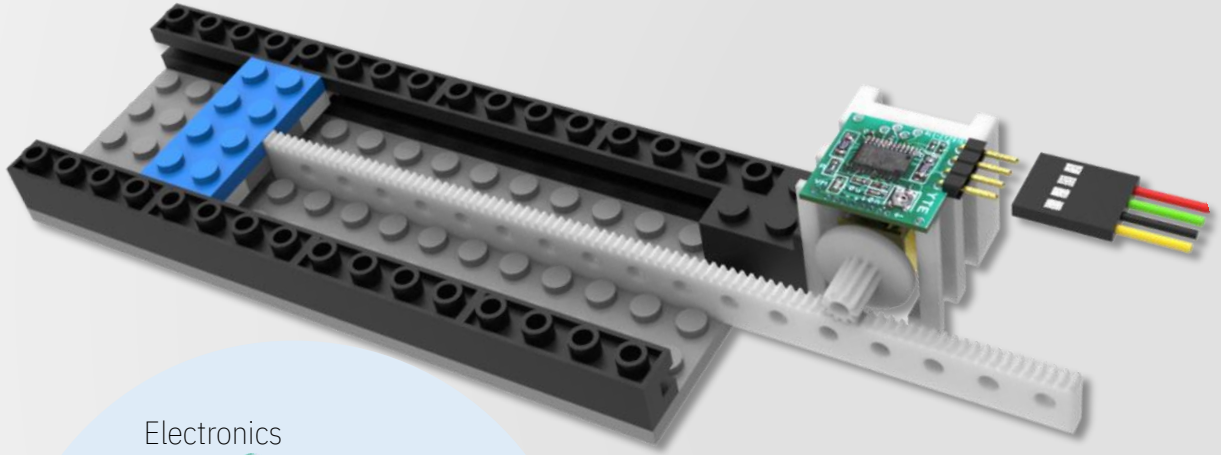


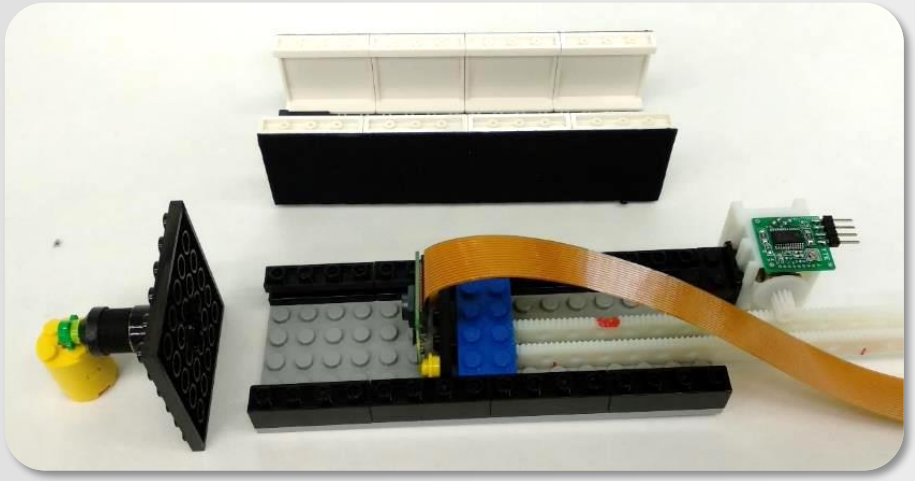


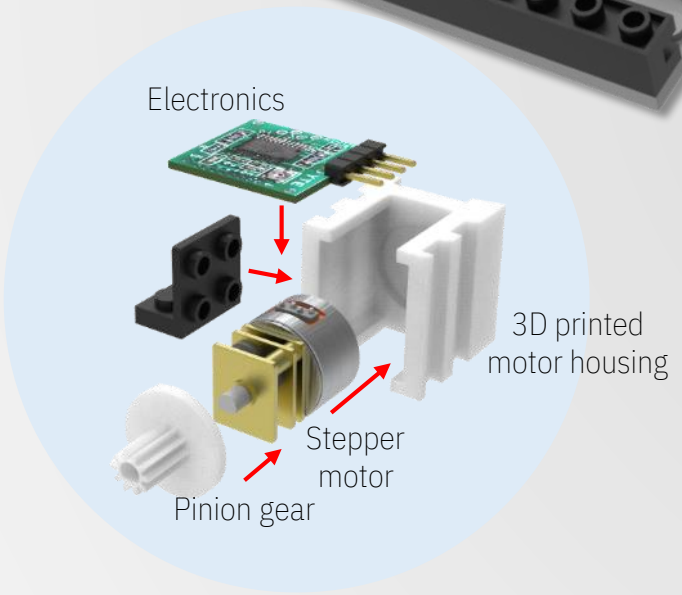
Issues:
- Difficult to assemble
- Side-to-side and up-and-down movements

Learning by failing – 4 (Tiny stepper motor + pinion gear + rack)

- XYZ stage: Moving a LEGO piece using a gear + rack combination and LEGO sliding guides
- Camera focus/magnification: Fully enclosed housing with a dedicated lens (same as the latest design)
- Electronics: Custom Arduino board using Attiny841 microcontroller and driver with microstepping (one board for each motor)
- Mechanical parts: LEGO bricks and 3D printed parts



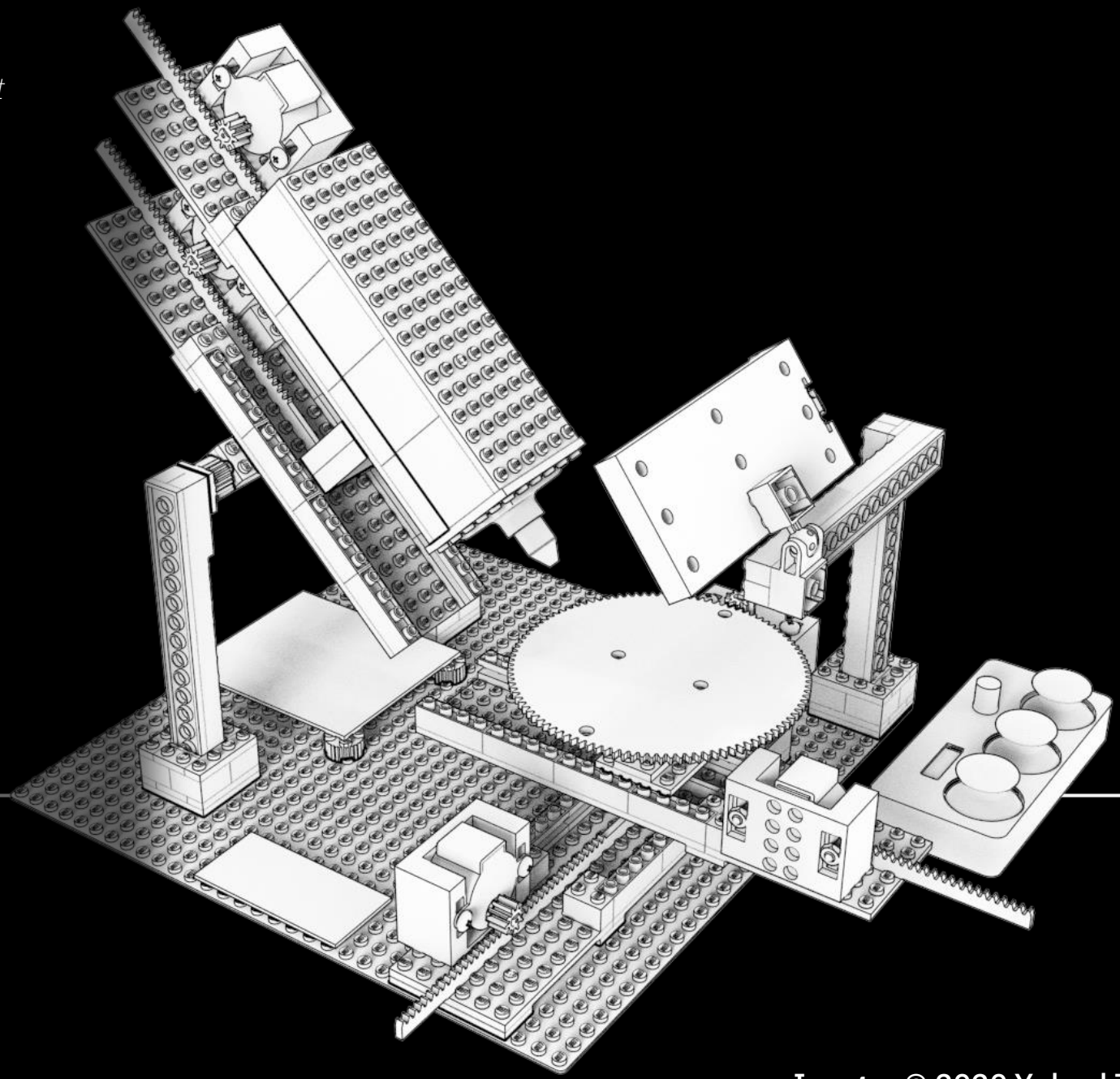




Issues:

- Requires high precision 3D printing (expensive equipment)
- Stepper motor: expensive and not easily obtainable in popular electronic stores

- *This project did not receive any technical or financial support from the companies mentioned in this document.*
- *LEGO® is a trademark of the LEGO Group of companies.*
- *Raspberry Pi is a trademark of the Raspberry Pi Foundation.*
- *Arduino® is a trademark of Arduino AG.*



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