Л.Н. Гумилев атындағы Еуразия ұлттық университетінің хабаршысы. Физика. Астрономия сериясы, 2021, том 137, №4, 61-70 беттер
http://bulphysast.enu.kz, E-mail: vest_phys@enu.kz

IRSTI: **55.30.51**

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An open-source robotic arm for educational purposes

Abstract: the dynamic spread of 3D printing technologies and open-source electronics prototyping platforms have enriched the possibilities of makers communities and the diversity of the approaches used within educational settings at different levels. Consequently, the complexity of the final projects has increased considerably. From one side, such a phenomenon may be regarded as extremely positive, given the continuous improvement and complexity of the actual general technological level. However, from the other side, the educational community may risk shifting the students' attention towards a higher level of abstraction, namely coding, while dealing with hi-techsolutions. Therefore, in the article, the realization of an open-source-based robotic arm for educational purposes is provided. In particular, the complete 3D printing of the constructional parts and the development of the Arduino platform based on controlling software and hardware is given. The work aims at describing the experience of the robotic arm realization with an educational emphasis on the hardware and software, providing an example of an adapted underlying arguments exposition.

Keywords: 3D Printing, Arduino, Educational Robotics, open-source project, open-source platform, LEAP motion sensor, EMG.

DOI: https://doi.org/10.32523/2616-6836-2021-137-4-61-70

Received: 26.11.2021 / **Accepted:** 30.11.2021

Introduction. The widespread proliferation of such platforms as Arduino, Raspberry PI, and micro:bit has already found their users at different levels [1, 2]. Whereas in the school and university ambients, these instruments serve as handy platforms to simplify students' effort when approaching microcontrollers coding [1-3]. In professional practice, they are still valid in terms of the acceleration of the development of the prototypes [4, 5]. Moreover, due to its simplicity and a wide range of readily available libraries for the wide variety of additional hardware, the platforms have attracted numerous researchers in terms of the daily routine experiments automation in a constrained period.

On the other side, the bloom of 3D printing technology we are facing today has essentially enhanced the list of the DIY instruments and designs at one's disposal. The active 3D printing communities provide freely available 3D designs of a wide range of complexity and utility [6-8].

When combined, the instruments outlined above enable the realization of the artifacts that may closely resemble their industrial counterparts [9, 10]. The last point, undoubtedly, is of particular importance within the context of the educational setting [11]. Because the students acquire the possibility not only to see the principles of the different artifacts working but, what is more appreciated, to see them within a single project [12]. The continuous evolution of the technologies in our modern world continuously evokes a continuous update for such a skill [13].

The article aims at sharing the experience of an open-source robotic arm realization. In particular, the authors cover the details and issues faced during the 3D printing of the robotic artifact and an auxiliary circuitry assembly. In addition, particular attention is paid towards the microcontroller (Arduino-based) code development, emphasizing educational pathway background.

Thus, the rest of the article is organized as follows. In the initial section, the instrument used during 3D printing is described. The accent is paid to the robotic arm constitutive parts 3D-printing, and the general strategy adopted. Next, the description of the electronic hardware used, and the functional scheme of the device follows. After, the presentation of the core part of the microcontroller software is provided. In both cases, i.e., electronic and software parts, the possible methodological strategies for the content delivery are emphasized. Finally, the possible advancements of the project are briefly outlined.

3D model and printing. The 3D printer used in work is Anycubic Photon Mono SE, a UV resin 3D printer. The printing technology realized in the instrument is LCD-based SLA based on the consecutive liquid UV-resin layers polymerization through UV LCD matrix. The 3D model of a robotic arm was borrowed from an open-source project developed by Italian design engineer Carlo Franciscone [14]. The model was adjusted following the characteristics of the parts and hardware available, particularly the diameter of the base carrying bearings.

Table 1 – Photon Mono SE 3D printer basic specifications

Parameter	Description/Value
Technique	LCD Shadow Masking
Light source	UV-LED (wavelength 405 nm)
Leveling	Ball pressure leveling
XY Resolution	0.051 mm 2560*1620 (2K)
Z-axis accuracy	0.01 mm
Suggested layer thickness	0.01~0.15 mm
Suggested print speed	MAX 80mm/h
Rated power	55W
Build Volume	130 mm (L) * 78mm (W) * 160mm (H)

The basic specifications of the printer are provided in the table below (Table 1). As opposed to widespread 3D printers with hot filament, a technique realized in this device, i.e., LCD shadow masking, enables the parallel development of objects, which, naturally, significantly reduces the overall printing time of the artifacts. Namely, once the objects to be printed are distributed on the platform surface (Figure 1), the geometries' development occurs simultaneously in parallel mode. The major drawback, in this case, is a relatively small build volume (see Table 1).

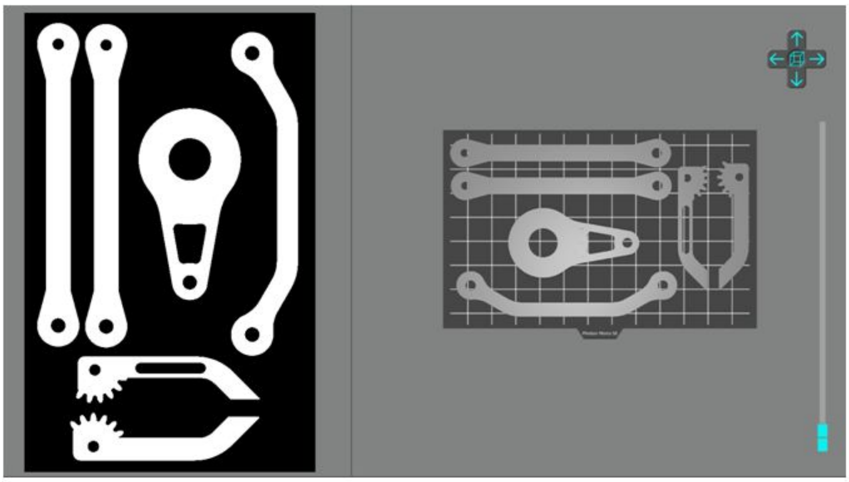


Figure 1 – The parallel development of the objects in a stack

Compared to the traditional fused deposition modeling (FDM-based), the LCD shadow masking provides a significant acceleration to the printing process. Moreover, when it comes to printing objects where the quality of the surface (smoothness) is not of primary importance (as in this case), the printing speed may be enhanced further by setting the single-layer thickness higher.

From the practical point of view, the primordial factor for the time spent on printing is the height of the highest object in the stack. Therefore, below the indicative times of printing depending on the object's height are provided (Figure 2).

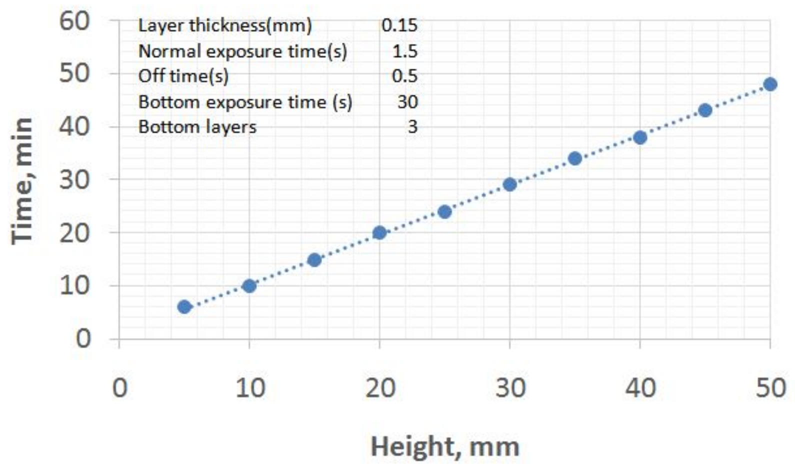


FIGURE 2 – The illustrative example of the 3D object development time dependence on height. In the legend, the printing parameters kept constant are listed

The final printing quality of an object fundamentally is defined by the printing dynamics, which, in the case of Anycubic Photon Mono SE is adjustable through setting the parameters summarised in the table below.

Thus, the overall printing time may be approximated by the following expression:

$$Time = \frac{Object\ height}{Single\ layer\ thickness} * (Normal\ exposure\ time + Off\ time) + \\ Bottom\ exposure\ time * Bottom\ Layers$$

At the practical level, the fundamental parameters to balance between are the following: the thickness of a single layer, which defines the surface roughness of the object, and the corresponding exposition time, which, at the first approximation, are proportionally related, i.e., the thicker the thickness value, the longer the exposition time of a single layer is supposed to be set. Notwithstanding the layer thickness suggested by the manufacturer (0.01-0.15 mm), from experience, it has been noted that the value of 0.4 mm might be affordable, provided the details' quality is not a primary factor, but the construction durability and the printing time. However, in this case, the user must pay attention to the exposition time because the insufficient exposition time does not permit the layers to adhere appropriately to each other, resulting in the structure exfoliation (Figure 3).

Another important aspect is dealing with the overhanging parts (Figure 4a). Again, the primary issue is the absence of a direct connection between the newly developing parts and the base structure at a particular time of geometry development (Figure 4b). Being overhanging, the parts, in this case, remain unattached to the structure but to the resin vat film, thus impeding (screening) the consecutive levels of development at these points. To avoid such a situation, generally, two bypassing strategies may be involved. The first one is the original geometry symmetrical cutting,

Table 2 – Printing parameters influence the final quality of the object

Parameter	Typicalrange	Comment
Layerthickness	0.01-0.15 mm	The thickness of a single layer defines the smoothness of the external surface, established in close relation to the normal exposure time.
Normalexposuretime	1.5 – 8 s	The time of a single layer exposure. If insufficient, the geometry risks not to be developed at all.
Offtime	0.5 – 3 s	The UV light-off interval between layers exposure.
Bottomexposuretime	20 – 80 s	The time necessary for the development of the bottom layers generally is measured in tens of seconds and is defined by the weight of the printed object to provide an optimal adherence of the structure to the plate.
Bottomlayers	3 - 10	Specifies the number of the bottom carrier layers with an enhanced adherence to the plate due to longer exposure time.

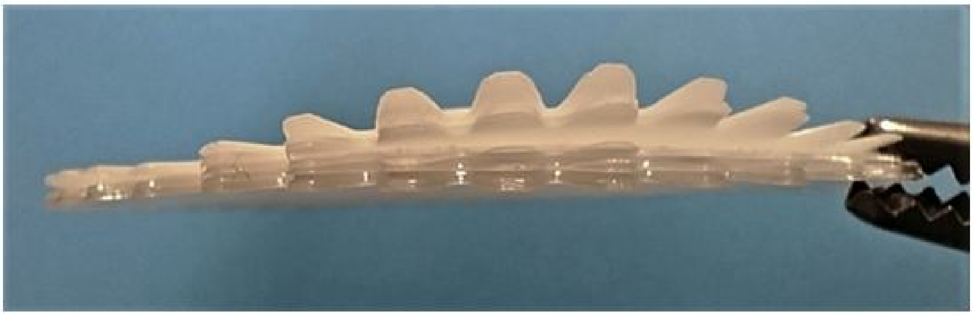


Figure 3 – An example of the 3D printing fails due to exfoliation

with subsequent gluing of the parts. The second is the use of supporting scaffolds, and the software supports the generation of which (both automatic and manual) – both in automatic and manual modes (Figure 4c).

Circuitry. In Figure 5, the functional scheme of the robotic arm is shown. As can be seen, the scheme is composed basically of two primary groups of elements: control and actuation. The control circuitry comprises the Arduino microcontroller, step motor drivers, joystick/switch for the step motors control, and the potentiometer for the servo motor control (gripper movement). The actuators are: three-step motors (the base and the arm movement), the servo motor, and the state-LED (not shown) used to discern between the two of the arm-controlling step motors active now and actuated through the switch. In addition, the power supplies for the micro-controller, potentiometer, joystick, servomotor, and the step motors (as the major consumers) are separated.

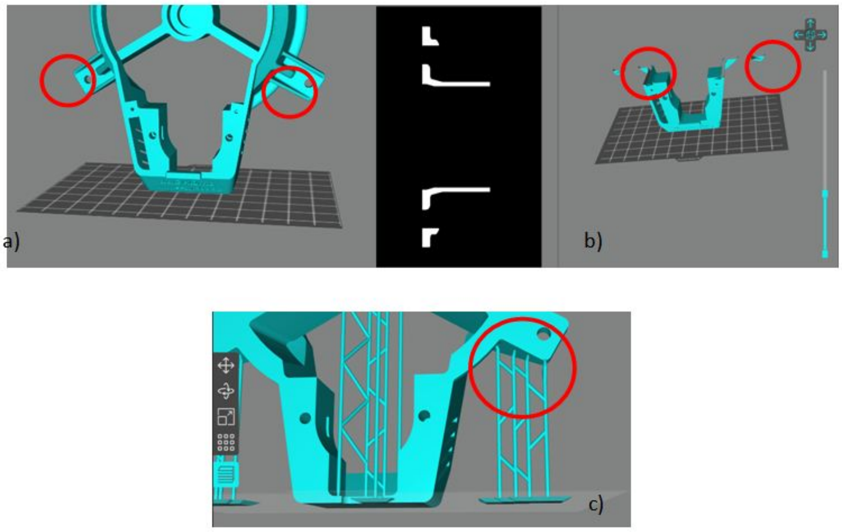


Figure 4 – a) the basement of the robotic arm with overhanging elements (marked in red); b) - the moment during 3D printing with no connection between the overhanging and the base structures; c) – supporting scaffolds generation

The standard low-cost 28BYJ-48 step motors with a ULN2003A Darlington array-based controller are used for robot control. The gripper is actuated through the DXW90 servomotor via a potentiometer. To minimize the quantity of the controlling hardware, the joystick is used both as the robotic arm controlling unit and the switch for the selection of the arm's left and right step motor independent actuation.

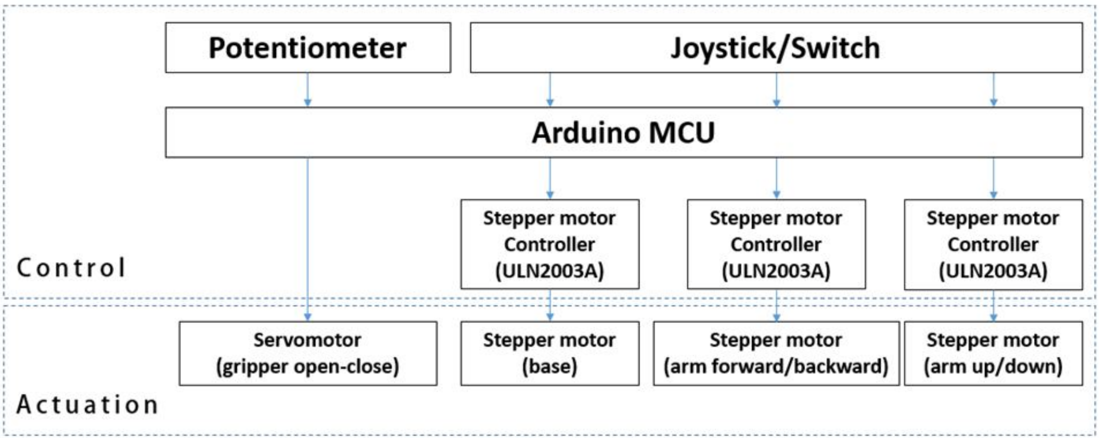
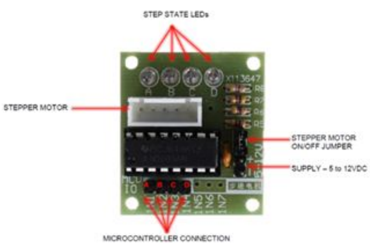


Figure 5 – The functional scheme of the robotic arm

Code. The primary aim of the microcontroller code is the control of three major components of the robotic arm: the base, the arms, and the gripper. Whereas the actuation codes for the first two components are basically the same, due to the same type of the stepper motors used, for the gripper being actuated through the servo motor, the actuation code was simplified by using the corresponding functions of the Arduino Servo library.

As is known, the great advantage of the open-source platforms is the possibility to choose from the great variety of ready-to-use libraries and built-in functions [15]. On the other side, using them or not remains up to the instructor's decision and directly depends on the educational scope [16]. The educational purposes dictated the selection of the auxiliary libraries to demonstrate the diversity of the tools at hand from one side and the eventual workarounds through the adoption of different coding strategies from the other. In this case, to keep the approach properly balanced (in terms of the use/non-use of the available libraries), it has been decided, in contrast to the servomotor control, to manage stepper motors avoiding the use of the dedicated libraries. In this way, from the authors' experience, the description of the stepper motor working principle becomes more transparent and efficient.

In particular, the stepper motor was controlled in a bit-wise mode within the code but using Arduino's digitalWrite function. Figure 6 the 8-step control of the stepper motor with the corresponding piece of the controlling procedures to clarify the idea further. As one can see, the microcontroller connection marked on the left image of the step motor controller printed circuit board with the red-letter A, B, C, D is controlled through the sequence of commands represented in the center of the figure. Moreover, as can be seen, it consists in sending the sequence of bits on controlling pins. Finally, as seen within the Arduino code, the controlling function representation on the right is provided.



Step	Command	IN4	IN3	IN2	IN1
A	01H	0	0	0	1
AB	03H	0	0	1	1
B	02H	0	0	1	0
BC	06H	0	1	1	0
C	04H	0	1	0	0
CD	0CH	1	1	0	0
D	08H	1	0	0	0
DA	09H	1	0	0	1

```
for(int i=_step;i<0;i++){
        setStep(0, 0, 0, 1);
        delay(_speed);
        setStep(0, 0, 1, 1);
        delay(_speed);
        setStep(0, 0, 1, 0);
        delay(_speed);
        setStep(0, 1, 1, 0);
        delay(_speed);
        setStep(0, 1, 0, 0);
        delay(_speed);
        setStep(1, 1, 0, 0);
        delay(_speed);
        setStep(1, 0, 0, 0);
        delay(_speed);
        setStep(1, 0, 0, 1);
        delay(_speed);
    }
void setStep(int a, int b, int c, int d)
{
    digitalWrite(Pin0, a);
    digitalWrite(Pin1, b);
    digitalWrite(Pin2, c);
    digitalWrite(Pin3, d);
}
```

Figure 6 – 8-step control of the stepper motor (see explanations in the text)

When it comes to the whole project's idea delivery in the class, the relative simplicity of the code in certain cases must be avoided, and a student is better to be guided to a deeper level of understanding. Moreover, the depth of the related material coverage has always to be adapted to the audience's specialization and be in accord with the goal of the course.

For example, the stepper motor controlling circuitry treatment may be started from the inner scheme of every driver, i.e., Darlington pair (see Figure 7a). With the corresponding discussion of the current amplification ratio that the scheme provides, emphasizing the inductive character of a load in this context. Nevertheless, depending on the audience specialization, the treatment of the argument may be reasonably started from the higher level of abstraction (Figure 7b), concentrating on the connection diagram and shifting the attention towards aneven higher level of the issue consideration code development. In short, whereas the approach to the argument following the classical scheme (from A to B) may be reasonable in the case of electronics engineering students, an immediate start from the second step may be an appropriate starting point for software engineering scholars.

All-assembled and future evolution directions. In Figure 8 the complete assembled robot is presented. The embedded QR-code contains a link to the video of the robot's performance. Being relatively simple, the performance testing did not face difficulties. The basic complication faced was a slight hacksaw adjustment of the mechanical pieces, particularly the gears. However, once all the

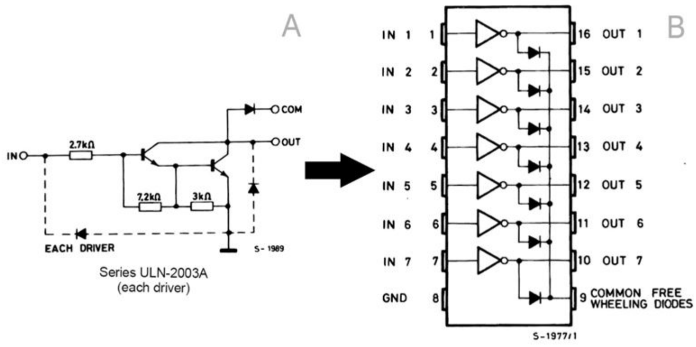


Figure 7 – Different levels of abstraction in the controller IC argument treatment. Adopted from [17]

pieces were fitted, assembled, and actuated, the overall movement of the structure resulted in being smooth and stable.

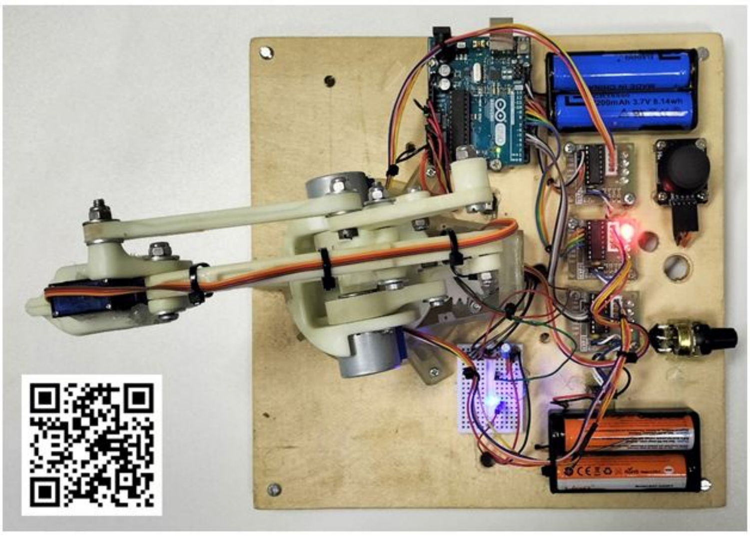


Figure 8 – The assembled robot in action (top view)

As to the future evolution of the robot, the authors intend to apply the additional hardware and software changes. In the first case, the actuation principle for the gripper may be based, for example, on an EMG sensor or LEAP motion sensor [18]. Fortunately, now, there is a quite vast diversity of options to choose from, both commercially available [19] and DIY variants [20]. As to the further project advancements, the authors plan to combine the system with the Oculus Quest virtual reality viewer.

Conclusion. The continuous technological development manifested in the widespread presence of open-prototyping electronics platforms, and 3D printing technology has naturally entered the educational context. An adequate and combined use of these instruments may significantly enhance the educational process, enabling students to acquire such highly acclaimed skills as systems thinking and project-based learningon the modern labor market [21, 22].

Thus, in the article, an example of a combined involvement of the instruments outlined above is presented. As one can see, the result does represent a quite complex artifact. Therefore, when introducing such kind of project, the adjacent learning pathway way can be varied significantly.

The authors hope that the information presented may be of utility within educational settings at different levels.

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Роботизированный манипулятор с открытым исходным кодом для образовательных целей

Аннотация. Стремительное распространение технологий трехмерной печати и платформ прототипирования электронных систем с открытым исходным кодом существенно расширило возможности сообществ мейкеров и разнообразие подходов, используемых в образовательных учреждениях на различных уровнях. В результате этого сложность окончательных проектов значительно возросла. С одной стороны, такое явление можно считать позитивным, учитывая постоянное совершенствование и сложность общего современного технологического уровня. Однако, с другой стороны, образовательное сообщество может столкнуться с риском избыточной концентрации внимания студентов на более высоком уровне абстракции, а именно: программировании, при изучении высокотехнологичных решений.

Ввиду вышеизложенного в статье представлена реализация роботизированного манипулятора с открытым исходным кодом для образовательных целей. В частности, подробно описаны 3D печать конструкционных деталей и особенности разработки управляющего кода и электронной схемы на основе Arduino. Работа содержит описание опыта реализации роботизированного манипулятора с акцентом на методические подходы к описанию аппаратного и программного обеспечения.

Ключевые слова: 3D печать, Ардуино, образовательная робототехника, открытый проект, открытая платформа, датчик движения LEAP, ЭМГ.

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Білім беру мақсатындағы ашық бастапқы кодымен робот манипулятор

Аннотация. Үш өлшемді басып шығару технологиялары мен ашық бастапқы коды бар электронды жүйелерді прототиптеу платформаларының қарқынды таралуы мейкер қоғамдастықтарының мүмкіндіктерін және әртүрлі деңгейдегі білім беру мекемелерінде қолданылатын тәсілдердің алуан түрлілігін едәуір кеңейтті. Нәтижесінде, соңғы жобалардың күрделілігі айтарлықтай өсті. Бір жағынан, қазіргі заманғы технологиялық деңгейдің үнемі жетілдірілуі мен күрделілігін ескере отырып, мұндай құбылысты оңдеп санауға болады. Алайда, екінші жағынан, білім беру қауымдастығы жоғары технологиялық шешімдерді үйрену кезінде студенттердің назарын абстракцияның жоғары деңгейіне, атап айтқанда, бағдарламалауға шамадан тыс шоғырландыру қаупіне тап болуы мүмкін.

Жоғарыда айтылғандарды ескере отырып, мақалада білім беру мақсаттары үшін ашық бастапқы коды бар роботы манипуляторды енгізу ұсынылған. Атап айтқанда, 3D басып шығару құрылымдық бөліктері және Arduino негізіндегі басқару коды мен электрондық схеманың даму ерекшеліктері егжей-тегжейлі сипатталған. Жұмыста аппараттық және бағдарламалық жасақтаманы сипаттаудың әдістемелік тәсілдеріне баса назар аудара отырып, роботы манипуляторды іске асыру тәжірибесінің сипаттамасы берілген.

Түйін сөздер: 3D басып шығару, Ардуино, білім беру робототехникасы, ашық жоба, ашық платформа, LEAP қозғалыс сенсоры, ЭМГ.

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