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DESIGN OF A LOW-COST 3D PRINTED EDUCATIONAL ROBOT

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Abstract. Industry 4.0 express the changes occurring in the industries in the last decades. These changes have been stimulated thanks to advances in innovations based on the combination of multiple technologies where sensors, machines, work tools and information technology are connected throughout the entire value chain. Aligned to this, Educational Robotics is seen as a study that is currently booming despite this teaching model being considered new in the Brazilian educational scenario. Robotics technology will play a fundamental role for the future of industries, through the development of techniques capable of stimulating the cognitive development of individuals, making them active in the stages of knowledge. Thus, justifying the development of useful tools for teaching and learning in robotics. This paper aims to materialize the theme of robotics, designing a prototype of a robotic arm with four degrees of freedom and a tool at the end effector. For that, a low cost 3D printed is designed and build using Arduino and the simulation implemented with Matlab®. The direct kinematics is solved using the Denavit-Hartenberg Covention. This paper presents a versatile product of low cost and small dimension, efficient, capable of being customized, compatible with the fundamentals of robotics, aiming to replicate the day to day of industry 4.0.

Keywords: fundamental of robotics, educational robotics, Arduino, industry 4.0.

1. INTRODUCTION

Industry 4.0 characterizes the transformations present in contemporary industries, the expression emerged at the beginning of the 21st century as a long-term strategy of the German government, since then, this industry model has been adopted by several countries in order to ensure the competitiveness of their industries (Santos et al., 2018 apud Kagerman, 2013). This new type of industry is causing significant changes in manufacturing and service processes, thanks to the advancement of innovations based on the combination of multiple technologies, forcing organizations to restructure the management of their businesses (Coelho, 2016).

Furthermore, this transition will manifest itself with the use of technological advances of the last decades in the areas of information technology and engineering, making sensors, machines, work tools and information technology connected along the entire value chain. This mutation is due to the pillars of industry 4.0 such as big data and data analysis, robotics, simulation, internet of things, cybersecurity, cloud computing, horizontal and vertical integrated systems, augmented reality and additive processes (Ribeiro, 2017 apud Rubmann et al., 2015). Figure 1 demonstrates the nine technological pillars of industry 4.0.
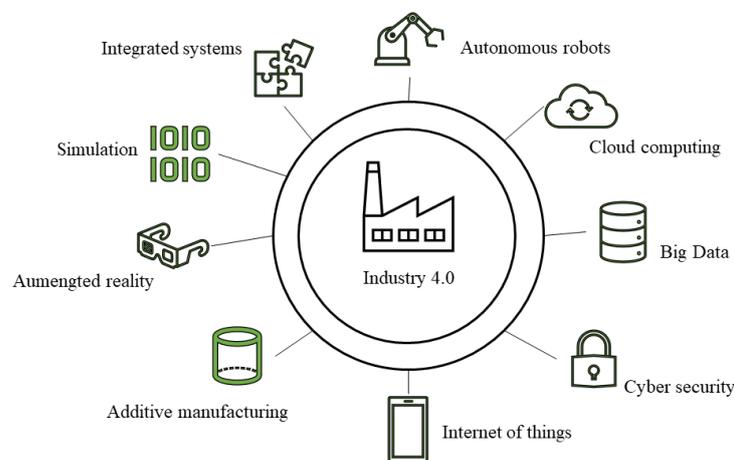

Figure 1. Pillars of the Industry 4.0.

Currently, robots are already being used to perform complex and unhealthy tasks, without the need for human supervision, being able to develop and coordinate a sequence of logistical and production tasks. Industry 4.0 will gradually introduce new business models, changing the way in which products and services are available to customers (Frantz et al. 2018). However, the modernizations will cause implications and improvements to the levels of information, connectivity and increased production efficiency, due to the collaborative innovation and connected and flexible production process throughout the distribution network and digitized services (Ribeiro, 2017).

In this context, educational robotics has emerged as an instrument that allows educators to verify in practice the theoretical concepts inherent to robotics, encouraging students to observe, abstract and invent. Applying multidisciplinary concepts for building prototypes, providing students with the application of theoretical knowledge in practice (Zilili, 204 apud Besafe, 2003).

As a result, the present paper aims to materialize the theme of robotics, designing and manufacturing a prototype of an industrial robotic arm with 4 (four) degrees of freedom with a tool at the end effector, of small size and low cost for didactic purposes, expressing the correlations of knowledge in robotics with the industry 4.0. The work is divided into the following structures. First, a review of educational robotics is presented. Then, the kinematic of the robot is described, showing the direct kinematic solution. Then, the Graphical User Interface designed in MATLAB® is presented. Next, the 3D printed robot are shown and finally the conclusions and the recommendation of future works are presented.

2. EDUCATIONAL ROBOTICS

Changes in the means of production and the social organization of work in modern society have occurred in line with the automation of production processes and the use of new technologies. Automation is associated with technologies that use programmed commands to execute a work process, being used on a large scale to replace human operators. One of the goals of automation is to remove the worker from unhealthy processes, as well as increase productivity and reduce production costs (Oliveira, 2019).

Therefore, the skills of workers who are going to face the new challenges must be in line with that of industry 4.0, which is the reason that characterizes education for the 21st century. The Maker education method (learning by doing) or "Hands on" education, a type of teaching that personalizes a space for creating and sharing knowledge for innovation (Alarcon, et al., 2018).

There are some robotics kits available to teach industrial robotics, however, its acquisition cost is high, which makes unfeasible in many educational institutions to buy one. Next, some kits discovered in the review of this work will be presented. Figure 2 shows a didactic workbench from the manufacturer Exsto that aims to develop programming and control skills for robotic arms. The workbench includes a robotic arm and moving mats. On the bench, it is possible to carry out a manufacturing simulation in four steps: separation, processing, storage and disassembly. The courseware provided includes the Educator's Guide, Student Guide and User Manual. The cost of this workbench is R$297.490,00 , consulted in February 2021.

Figure 2. Workbench with an industrial robot (Exsto, 2020).

Another workbench to teach industrial robots is presented in Figure 3. Described as Mobbot, is a mobile robotic system for feeding machines, having as its main characteristic the flexibility and efficiency in the loading and unloading processes. The total cost of this equipment, consulted in February of 2021 is R$ 496.900,00.

Figure 3. Workbench with an Kuka industrial robot (Auttom, 2020).

As shown in this section, workbenches with industrial robots still have a high cost to purchase in Brazil. For many educational centers, this cost makes the acquisition of such equipment an impediment. The development of a low-cost robot for didactic application is presented in the next sections of this paper.

3. KINEMATICS OF THE ROBOT

To obtain the set of equations that characterize the kinematics of a joint associated with the next joint, the Denavit-Hartenberg (D-H) notation was applied. This procedure obeys the concepts of homogeneous transformations inherent to positive rotation following the right hand rule. The z axis represents the action axis (rotation) of each joint (Siciliano et al., 2010).

Through the D-H convention (Figure 4), the four parameters that constitute the homogeneous transformation matrix were determined, namely: the joint rotation angle θ_i, the rotation angle between the joints α_i, the length of the links a_i, and the joint displacement d_i. These parameters are established based on the Cartesian coordinate system.
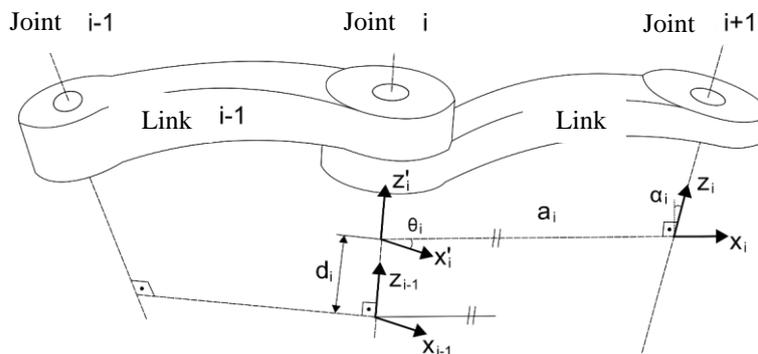

Figure 4. Denavit-Hartenberg convention (Sicialiano et al., 2011).

The D-H convention is one of the known ways to outline the methodology for obtaining the position of the coordinate systems of each link. In this approach, it is necessary that the manipulator kinematic chain modeling is done through the transformation of rotation and translation only in the x and z axes, obeying the constructive characteristics of the robotic arm, as shown in Figure 5.
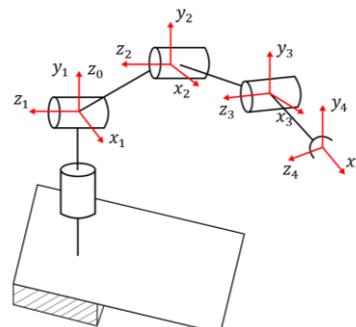

Figure 5. Schematic representation of the reference position of the designed robot.

On the other hand, Table 1, presents the geometric diagram that associates the position vectors of the robot joints to their respective vector of position coordinates and end effector orientation. This represents the angular translation values of the Cartesian coordinates of each joint of the robotic arm.

Table 1. D-H parameters of the robot

Link	$a_i[mm]$	α_i	$d_i[mm]$	θ_i
1	0	$-\pi/2$	102.5	θ_1
2	63.5	0	0	θ_2
3	63.5	0	0	θ_3
4	107.56	0	0	θ_4

After obtaining these values, the homogeneous transformation matrix was determined, thus, the position and orientation parameters of the Cartesian coordinates of two consecutive joints were obtained, this one being represented by means of Eqs. (1) and (2).

$$A_i^{i-1} = Az(d_i)\, Az(\theta_i)\, Ax(\alpha_i)\, Ax(\alpha_i) \tag{1}$$

$$A_i^{i-1} = \begin{bmatrix} cos\theta_i & -sen\theta_i cos\alpha_i & sen\theta_i sen\alpha_i & a_i cos\theta_i \\ sin\theta_i & cos\theta_i cos\alpha_i & -cos\theta_i sen\alpha_i & a_i sen\theta_i \\ 0 & sen\alpha_i & cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

4. GRAPHICAL USER INTERFACE

The Graphical User Interface (GUI) was designed in MATLAB®. First, a folder was created at the root of MATLAB® called 'robot_simulator', inside this folder two more folders were created, the 'functions' folder, which will store the main direct kinematics and interface scripts GUIDE graphics. The 'robos' folder, where folders named according to the type of handler to be programmed will be allocated, inserting the script 'parametros.m' and the STL files of that handler. This folder hierarchy is shown in Figure 6.

Once the kinematic parameters of the manipulator had been defined, the process of obtaining the script 'parametros.m' began, responsible for reading all the robot information, including the D-H parameter, the files STL and the corresponding manipulator degree of freedom.

Subsequently, the script 'calcula_dh.m' was created, which is responsible for calculating the homogeneous transformation matrix from the D-H parameters of the manipulator, Eq. (2). Scripts available in the MATLAB® Robotics Toolbox [1]for Education library were also used.
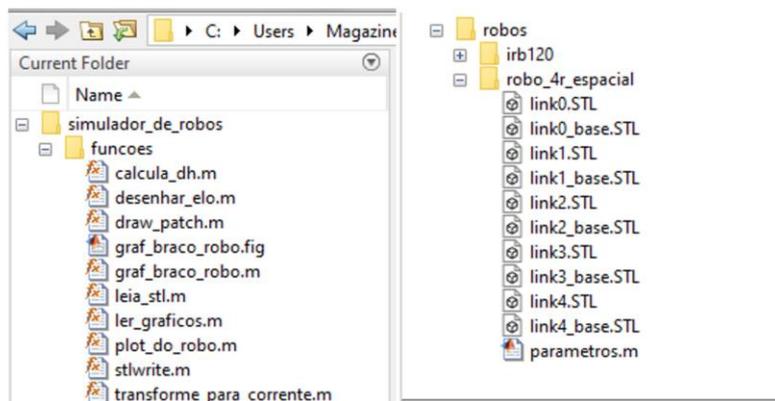

Figure 6. Folder hierarchy with the scripts of the GUI in MATLAB®.

These scripts have the function of calculating the new coordinates of each link according to the vertices of the STL files and the homogeneous transformation matrices, reading all the vertices contained in the STL files, reading the STL files and saving the coordinates of the vertices and the normal vector of the robot global variable, plot the robot links on the GUIDE screen, save the patch STL files or surface data, and change the coordinates of the points stored in the STL files. These scripts are available for download through the link https://bit.ly/tcc_unifebe_lucas.

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[1] https://arvc.umh.es/arte/

To simulate the robot's kinematic behavior, the script 'graf_braco_robo.m' was created, responsible for presenting the graphical interface. This script is used to program the sliders responsible for rotating the manipulator joints and simulating the robot's direct kinematics. Figure 7 illustrates the GUIDE graphical interface programming panel generated through the Toolbox library of MATLAB®.
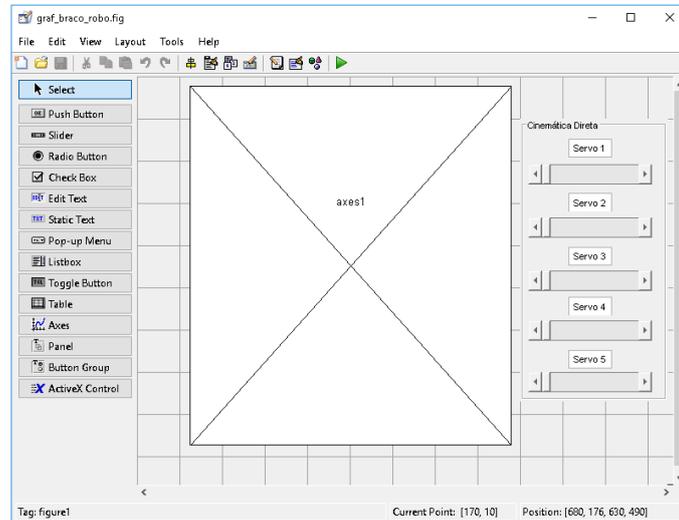

Figure 7. GUI designed in MATLAB®

In this interface, the user must adjust the values of each joint represented by the 'Servo 1', 'Servo 2', 'Servo 3', 'Servo 4' and 'Servo 5' sliders. In this way, the user will be able to simulate the robot's kinematic behavior, predicting its trajectory based on the Denavit-Hartenberg parameters. It should be noted that at this stage of the work, the preliminary design of the robot was completed.

In order to verify whether the manipulator respects the Denavit-Hartenberg parameters, a CAD assembly of the robot was generated in the STL extension, where each manipulator member (base, arm, forearm and wrist) was renamed according to the standards (link0.STL, link1.STL,...linkn.STL).

First, the files 'link0.STL', 'link1.STL', 'link2.STL', 'link3.STL' and 'link4.STL' (base, arm, forearm and end effector respectively) were inserted into a folder created in root of the MATLAB® named according to that robot. Next, the script 'parametros.m' was executed, the software reads and loads the robot's STL variables as shown in Figure 8.

Figure 8. STL reading in MATLAB®.

Later copies of the previous files were created by renaming them as 'link0_base.STL', 'link1_base.STL', 'link2_base.STL', 'link3_base.STL' and 'link4_base.STL', these files will have their coordinate system referenced in base, and when executing the function 'transform_to_current(robo,1)', the software will overwrite the coordinate system of the STL files 'link1', 'link2', 'link3' and 'link4' to the current coordinate system.

To finish this procedure, execute the script 'parametros.m' again, so the coordinate system of the manipulator will be configured for the current coordinate system, being able to execute the graphical interface of the manipulator, the script 'graf_braco_robo.m'. Thus, the programming of the robot's kinematics was concluded.

5. 3D PRINTED ROBOT DESIGNED

The product resulted in a robot with 4 degrees of freedom (DOF), with a tool at the end effector, being classified according to its geometry as a 4R spatial manipulator. The robotic arm specifications are shown in Table 2. The device is exclusively developed for the practice of teaching robotics and can be widely used in educational activities with students from elementary to higher education. Figure 9 shows the CAD model of the developed manipulator.

Table 2. Specification of the 4R spatial manipulator

Specifications			
Robot version	Workin range (m)	Number of axes	Mounting
RobFebe 1	0.15	4	Base link
Controller	Arduino Uno with Sensor Shield V5.0		
Movement			
Axis Movement	Workin range	Servo	Torque (kg.cm)
Axis 1	-60° to + 60°	MG995	8.5
Axis 2	-60° to + 60°	MG995	8.5
Axis 3	-60° to + 60°	MG995	8.5
Axis 4	-60° to + 60°	MG995	8.5
Tool	-90° to + 90°	SG90	2.5

The designed robot has the purpose of admitting the customization of its application, for that, it is only necessary to develop a tool according to the intended functions. In this way, the educator will develop in his students competences and abilities for the elaboration of work and research, critical sense, overcoming adversities and logical reasoning, solving problems belonging to the industries of the future. This feature is seen as a differential of the product presented here.

As for the manufacturing process used, it proved to be able to produce complex details in an easy and economical way. According to Rozenfeld et al., (2006), the cost of the manufacturing process is usually attributed as the most important. This is directly affected by size, shape, production rate, tolerance and surface finish requirements. Followed by the cost of tooling, development time needed to start production, the effect of the workpiece material on the tool, labor, among others.

The time elapsed for printing the pieces proceeded in approximately 40 hours. Considering the hourly value of the 3D printer, something around R$10.00, plus the costs of obtaining actuators and electronic devices, an estimated cost of approximately R$680.00 was accounted for in product manufacturing. Figure 10 depicts the robotic arm developed.
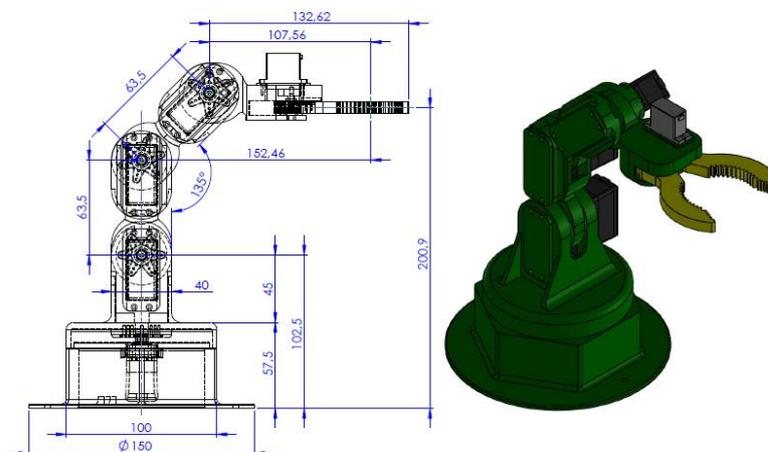

Figure 9. CAD representation of the robot and the dimensions in mm.

In this context, the additive manufacturing process proved to be effective, making the acquisition of special or value-added tools unnecessary. The pieces were printed in lactic polyacid resin (PLA), a raw material used in most 3D printers, and this material is available at the university laboratory. The cost of production proved to be minimal, and the time

needed to start implementing the project was immediately revealed. This qualifies the project as having a small purchase price.
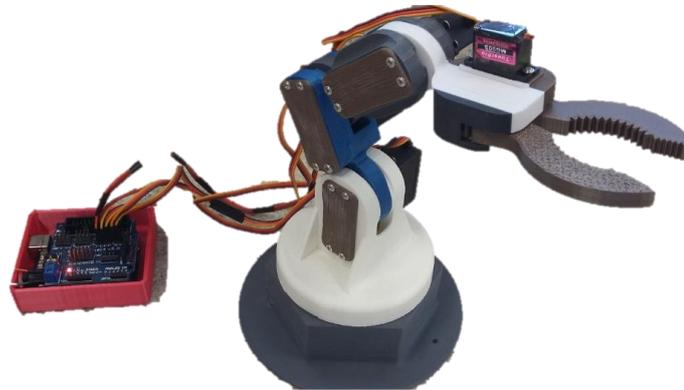

Figure 10. 3D printed robot manipulator with 4 DOF.

The development of the fundamentals of robotics was carried out through the script 'graf_braco_robo.m'. Being responsible for graphing on the screen the GUIDE graphical interface (see Figure 11) containing a graphical representation in 3 dimensions of the robot, with their respective sliders, Servo 1, Servo 2, Servo 3 Servo 4 and Servo 5 (base , arm, forearm, wrist and gripper), in which the manipulator joints are rotated.

Thus, the graphical interface requests the user the angle values of each manipulator joint for a robot position in three-dimensional space. The scripts read the measurements of each link, and perform the calculation of the homogeneous transformation matrix (Eqs. (1) and (2)) providing the user with the position and orientation of the effector expressed in the current coordinate system.

(a)   (b)
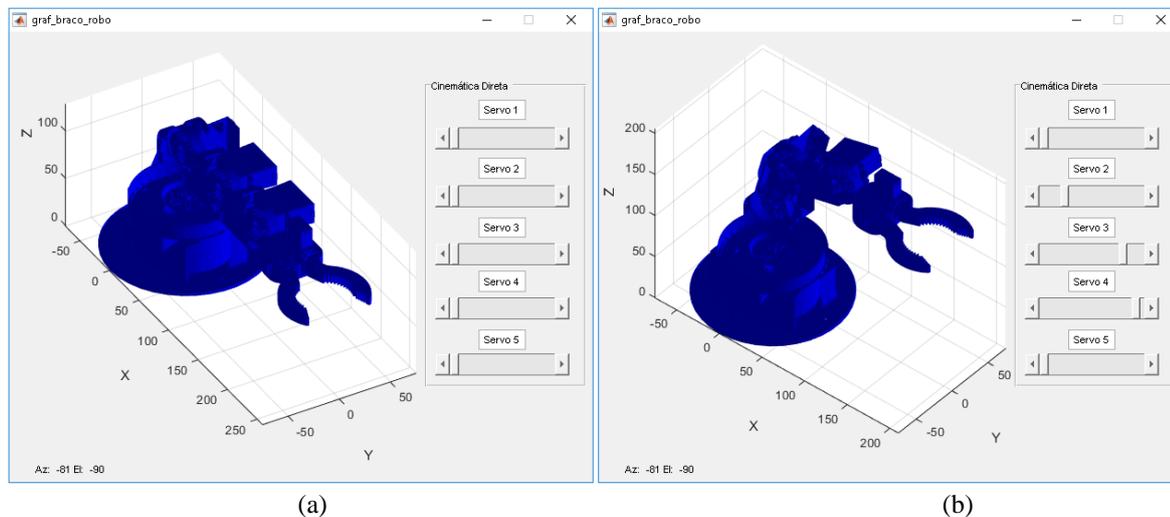
Figure 11. Graphical user interface do simulate the direct kinematic (a) initial posture and (b) new position using the sliders of the GUI.

The tests proved that the handler corresponded to the proposed objective. Representing via graphical interface that the robot obeys commands based on direct kinematics programming, based on the D-H parameters prescribed for the manipulator. Thus, with this work it is possible to simulate a situation in which the manipulator is in an initial position (see Figure 11 (a)), leaving for another position in space (see Figure 11 (b)) through the sliders Servo 1, Servo 2, Servo 3, Servo 4 and Servo 5, being responsible for the movement of the base, arm, forearm, wrist and claw respectively.

6. CONCLUSIONS

Educational robotics has been shown to be an important tool for logic and programming development for students, and has become a great tool to reduce the levels of social inequality in our country. In addition, the application of tools such as educational robotics has great potential to facilitate the development of our industries, belonging to the areas of technology and production of high value-added products and services.

Thus, educational robotics can be considered a universe of learning in expansion, its application can have a positive impact on human development standards, and can be adopted as a new learning and professional training strategy.

To materialize this project, it was necessary to apply several theories based on different areas of human knowledge, including: science, physics, mathematics, engineering, computing, among other areas that make up the curriculum of human knowledge. In this way, it was possible to originate a versatile and efficient product of small size and low manufacturing cost, capable of being customized following the fundamentals of industrial robotics, in order to reproduce the daily routine of Industry 4.0.

Therefore, in this work it was possible to materializing the robotics theme through an applied research, giving rise to a robotic arm simulacrum, of small dimension and low cost for didactic purposes. In order to train professionals for the future of industries, the infamous era of industry 4.0.

As a theme for future work, it is suggested the creation of a didactic bench that enables the study of operations and basic programming of a robotic system. Material handling in a flexible manufacturing cell, quality control, production and customization of a work cell. Replicating an industrial activity in which the manipulator interacts in real time with several devices and equipment simultaneously, aiming to reproduce a practical application of industry 4.0.

7. REFERENCES

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