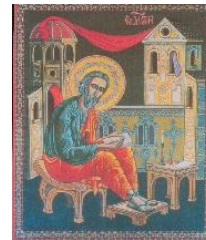




**БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ
ИНСТИТУТ ПО РОБОТИКА**

България, София 1113, ПК 79, ул. "Акад. Г.Бончев", Бл.2,
Тел. (+359 2) 8703361, 4053055, Факс: (+359 2) 4053061

**Почетен член на
"Съвета на Европейската научна и културна общност"**



Borislava Lyubomirova Kostova, MSc., PhD Candidate

**Integrating 3D printing, robotics and emerging
technologies for the purposes of education**

ABSTRACT

**Of
DISSERTATION**

for the award of the educational and scientific degree

"Doctor of philosophy (PhD)"

***Doctoral degree: "Application of the principles and methods of
cybernetics in various fields of science"***

Scientific supervisors:

Prof., PhD Ivan Chavdarov

DSc. Professor (Associate) Galya Georgieva-Tsaneva

Sofia, Bulgaria, July 2026

The dissertation has been discussed and approved for defense at an extended meeting of the “Robotic and mechatronic intelligent sySTEAMs” (RiMIS) section at the Institute of robotics – Bulgarian Academy of Science, held on 13/07/2026 in accordance with order № 85/07.07.2026, issued by the Director.

The doctoral candidate is employed at the Institute of robotics – BAS, located at 1113 Sofia, Bulgaria, Acad. Georgi Bonchev Str., Bl. 2. She was enrolled as a part-time PhD student in the “Robotic and mechatronic intelligent sySTEAMs” (RiMIS) section at the Institute of robotics – BAS with order № 86/23.06.2023, issued by the Director, with duration of the educational and scientific degree from 1st July 2023 till 1st July 2027.

The scientific experiments for the purposes of the dissertation were conducted at the Institute of Robotics, Bulgarian Academy of Sciences, the 19th Secondary School "Elin Pelin" in Sofia and the National Professional High School "Dimitar Talev" in Gotse Delchev, Bulgaria. The study was approved by the Ethical Committee for Scientific Research (ECSR) of the Institute of Robotics, Bulgarian Academy of Sciences.

The dissertation comprises a total of 153 pages and includes: an Introduction, five chapters, a Conclusion, Future work directions, Contributions of the dissertation, Bibliography containing 137 references, 9 tables and 44 figures. The numbering of the tables, figures, chapters, sections and subsections in the abstract corresponds to that in the dissertation.

The materials relevant to the dissertations are available at the administrative office of the Institute of robotics – BAS, block 2, room 406.

Scientific jury:

Internal members:

1. Prof., PhD Tanyo Tanev
2. Associate Prof, PhD Neda Chehlarova

Substitute member: Prof., PhD Maya Dimitrova

External members:

3. Prof., PhD Nikolay Stoimenov IICT – BAS
4. Prof., PhD Ivan Yachev – TU, Sofia
5. Prof., PhD Valentin Mateev – TU, Sofia

Substitute member: Associate Prof, PhD Mila Ilieva – Obretenova, UMG, Sofia

Author: Borislava Lyubomirova Kostova

e-mail: borislava.kst@gmail.com

Title: Integrating 3D printing, robotics and emerging technologies for the purposes of education

General characteristics of the dissertation

Research domain

The research domain addressed by this dissertation is the application of emerging technologies for educational purposes. Specifically, the dissertation examines the use of 3D modelling, 3D printing, robotics, and chat bots with artificial intelligence (AI) across three principal educational contexts: general education, specialized outside the STEAM disciplines, and focused specifically on the applied arts, and education for students with special educational needs (SEN).

The subject of the research comprises:

- A protocol for conducting a STEAM educational activity, integrating the use of AI as a teaching support tool, 3D-printed educational models, and instructional scenarios for the NAO humanoid robot. The protocol is presented in Chapter 2.
- An approach for automated 3D modelling of educational objects. The approach incorporates the automated generation of 3D models within the AutoCAD environment, followed by their fabrication using a 3D printer. The algorithm of the approach offers three key aspects of personalisation: (1) adaptation to the individual user, (2) adaptation to the writing instrument, and (3) visualisation of educational principles. The approach is presented in Chapter 3.
- A new software program for the automated 3D modelling of rings in the AutoCAD environment, developed based on the proposed approach. The application, named "rings," is presented in Chapter 4.
- A new software program for the automated generation of a 3D model of a personalized writing aid for students with impaired fine motor skills, developed based on the proposed approach. The application, named "pinky," is presented in Chapter 5.

Relevance of the problem

The STEAM model envisions interdisciplinary education bringing together Science, Technology, Engineering, Arts and Mathematics. It has become the leading pedagogical paradigm aimed at fostering key professional and soft skills for today's labour market. Despite the widespread recognition of the STEAM approach, its practical integration into mainstream general education continues to face a number of systemic challenges and barriers documented in the existing scientific literature.

The implementation of the STEAM approach is further constrained by its predominant focus on extracurricular activities and specialized clubs, which primarily attract students who already demonstrate a strong prior interest in STEM (Science, Technology, Engineering, and Mathematics). This limitation gives rise to significant socioeconomic concerns by restricting broader participation in STEM education. Furthermore, there is a lack of approaches for adapting and personalizing educational content to meet the interests and learning profiles of students specializing in disciplines outside the STEM fields. Equally lacking are methods for reducing the cognitive barriers associated with learning complex software tools.

Substantial research gaps are also evident in the field of education for students with SEN. Although previous studies have demonstrated the educational benefits of incorporating 3D printing, robotics, and chat bots with AI into learning activities for this group of students, the initial technology adoption remains associated with considerable cognitive barriers preventing a more widespread use by therapists, teachers, and students alike. In addition, there is a pressing need for low-cost, adaptive, and personalized assistive devices designed for educational purposes that can accommodate the evolving individual needs of students with SEN. Such solutions have the potential to facilitate greater educational inclusion while enhancing the accessibility and effectiveness of technology-supported learning environments.

Definition of the Problem

There is currently no established protocol for their systematic application in the design of interdisciplinary STEAM lessons. At present, the implementation of the STEAM methodology largely depends on the individual teacher's interdisciplinary expertise and personal interests. Additional challenges to the effective implementation of STEAM education include the limited time available for lesson preparation and the need for specialized technological training for teachers.

There is a lack of accessible software programs that enables the automated use of 3D modelling and 3D printing, the third most widely adopted technology within STEAM education. Such programs could not only reduce the cognitive barriers associated with the initial acquisition of CAD and 3D modelling skills but also provide a high degree of personalization and adaptation to accommodate the diverse needs, abilities, and interests of individual learners.

There is a limited number of studies investigating the potential of 3D printing for the personalization of assistive devices for students with SEN. There is also a lack of empirical evidence regarding the educational effectiveness of such personalized assistive solutions.

Objectives and tasks of the dissertation

The aim of this dissertation is to develop, validate, and evaluate an approach for integrating 3D modelling, 3D printing, robotics, and chat bots with AI to enhance the effectiveness of STEAM educational activities.

To achieve this aim, the following research objectives are defined:

1. To develop, validate, and evaluate a protocol for the automated design and implementation of a STEAM educational activity incorporating AI as a teaching support tool, together with the use of 3D-printed educational models and instructional scenarios involving an educational robot.
2. To propose an approach for the automated generation of personalized 3D-printed models and to investigate their application for educational purposes.
3. To develop a software program for automated 3D modelling in the AutoCAD environment, based on the proposed approach and intended for the creation of decorative objects. Using the developed application, to design and evaluate 3D-printed models for teaching applied arts. Furthermore, to investigate the application of the proposed approach, the developed software program, and the resulting 3D-printed objects within the educational process.
4. To investigate and evaluate the effectiveness of 3D-printed assistive writing devices for students with SEN. To analyse approaches for designing personalized assistive devices, including methods for user adaptation, acquisition of individual anthropometric measurements, and determination of the key geometric parameters required for device customization.
5. To develop a software program for the automated generation of a 3D model of a personalized writing assistive device (WAD) for students with impaired fine motor skills. The application will be developed on the basis of the findings and design principles established in Objective 4.

Research methodology

In response to the research limitations and gaps identified in the scientific literature, this dissertation proposes (1) a protocol for the automated design and implementation of interdisciplinary STEAM lessons, based on the synergistic integration of 3D technologies, social robotics, and generative artificial intelligence (AI), and (2) an approach for the automated generation of personalized 3D-printed models and their application for educational purposes.

The proposed protocol contributes to the advancement of the practical toolkit available to STEAM educators by providing a structured framework that facilitates both the understanding of the STEAM methodology and its broader and more effective implementation in educational practice. To the best of the author's knowledge, no comparable practical and automated protocol has been reported in the literature at the time of this research. The protocol was validated in real classroom environment through a pilot experimental study investigating its effect on student engagement.

The proposed approach for the automated 3D modelling of personalized educational tools extends the current state of the art in several important respects:

- Universalization through the principles of a simplified and minimalist design, enabling rapid manufacturing, iterative development, and efficient personalization. The approach employs a standardized base geometry for CAD design, thereby overcoming the limitations associated with 3D-scanning-based methods commonly used in existing research.
- Enhanced adaptability of educational objects by extending personalization beyond adaptation to the individual user to include adaptation to different external objects like writing tools, thereby increasing their versatility and practical applicability.

The proposed approach was validated through the development of two software programs for automated 3D modelling. The first application, "rings," was developed to support education in the visual and applied arts, while the second application, "pinky," was designed for the automated generation of personalized 3D models of WAD for students with SEN, particularly those with impaired fine motor skills.

Content of the dissertation

I. CHAPTER 1:

Review of the existing scientific literature on the application of 3D printing, robotics, and chat bots with AI for educational purposes.

1.1. The application of 3D printing, robotics, and AI in a general education STEAM context.

1.1.1. 3D printing

3D printing technology has widespread application in STEAM education for the purpose of visualizing fundamental concepts across various disciplines and demonstrating their practical applications. It enables learners to acquire skills in computer-aided design (CAD), interact with 3D-printed objects, or combine both approaches within the learning process.

The main advantages of this technology are associated with its cost-effectiveness in the production of customized and complex forms in small quantities, as well as its environmental sustainability. Certain 3D modelling software solutions, such as AutoCAD, enable process automation, thereby reducing design time, overcoming cognitive barriers associated with entering a new field of knowledge, and enhancing students' motivation and digital competencies.

Significant limitations of the application of 3D printing technology in education include relatively slow manufacturing processes, initial investments required for equipment and consumables, as well as the qualification barriers, learning curve and limited time available for educators to acquire proficiency in specialized CAD modelling software.

1.1.2. Educational robots

Robotic systems find application in various stages of the educational process. STEAM activities often include pre-assembled platforms, modular or 3D-printed robotic kits, social humanoid robots (such as NAO), and educational robotic toys. Educational robots represent an interactive tool for teaching programming, engineering, foreign languages and various other disciplines through integrated software environments such as Choregraphe or Python.

A major advantage of these systems is their adaptability to different scenarios and levels of proficiency in a given subject. Educational robotics are reported, in the existing scientific literature, to contribute to the enhancement of cognitive abilities, including memory, logical reasoning, and creativity, while also fostering teamwork skills and complex problem-solving competencies. At the same time, student motivation and attention are seen to increase. This effect is particularly evident among students with lower academic achievement and learners with SEN.

The main limitations of robotics integration in education include the relatively high market costs, technical complexity associated with programming without prior training, and the need for ongoing maintenance and technical support. Furthermore, there remains a shortage of adequately trained educators possessing the necessary technical and pedagogical competencies for the large-scale implementation of robotic systems in educational practice.

1.1.3. AI

Generative AI language models are emerging as a new form of educational technology within the established research field of Artificial Intelligence in Education (AIED).

The primary advantage of integrating AI into education is its ability to rapidly personalize learning content according to individual student needs, combined with 24/7 accessibility that supports self-regulated learning. Its implementation can also provide significant benefits for educators by assisting with lesson preparation and administrative tasks, thereby reducing psychosocial risks associated with the teaching profession, such as occupational stress and professional burnout.

The main limitations include the risk of excessive dependence on AI systems, potential reductions in critical thinking skills, and superficial knowledge acquisition. The technology also presents risks related to the generation of inaccurate, misleading, or biased information. Furthermore, the requirement for reliable internet access and the use of paid subscription models may contribute to inequalities in access to AI-based educational resources.

1.2. The application of 3D printing, robotics, and AI in specialized arts education.

Personalization of learning and alignment with the specific motivational profiles of different student groups can contribute to increasing and sustained interest in science and technology-related disciplines. The implementation of targeted and personalized STEAM activities has a positive impact on the attitudes of students without a prior interest in STEM and stimulates their willingness to pursue academic and career development in these fields. The practical application of this approach within specialized educational programs demonstrates that connecting learning experiences with the specific interests and identities of participants significantly enhances their motivation to engage in interdisciplinary education.

1.2.1. 3D printing

CAD technologies and 3D printing are widely applied in specialized arts education. A key advantage of 3D printing is its potential to serve as an introductory technology, facilitating students' engagement with digital design, engineering concepts, and technology-enhanced creative processes. Among the main limitations and challenges are the lack of open-source and adapted software solutions, and the insufficient availability of detailed implementation protocols for their integration into educational activities.

1.3. The application of 3D printing, robotics, and AI for students with SEN.

1.3.1. Robotic systems

Robotic assistive technologies (AT) are widely applied in both educational and therapeutic contexts to support the academic development, speech and language therapy, and daily living activities of students with SEN. The high potential of low-cost, personalized assistive devices, manufactured through 3D printing, represents an effective solution for addressing existing barriers in this field.

1.3.2. AI

AI is applied in the education of children with SEN as a tool for creating personalized and adaptive learning environments. One of the main advantages of AI-based systems is their ability to analyze students' behaviour and responses in real time and identify optimal pedagogical strategies.

The key challenges associated with the implementation of this technology in special education include data privacy protection and the verification and filtering of accurate information generated by AI systems, particularly in the context of neurodiverse groups of learners. The highest effectiveness in the educational process is achieved through collaboration among teachers, therapists, users, AT, and AI-based systems.

A research gap has been identified regarding the development of practical implementation protocols and automated systems that can reduce the time required for training and facilitate the overcoming of cognitive barriers associated with acquiring new technological knowledge.

1.3.3. 3D printing

3D printing is increasingly established as a low-cost assistive solution with significant educational potential, providing accessibility and inclusive education. It enables the production of personalized educational objects and assistive devices tailored to individual user requirements, such as writing grips. Assistive writing devices (WADs) have been reported to support the development of hand–eye coordination in children with cerebral palsy (CP). However, existing software programs for automated 3D modelling of WADs are characterized by limited functionality. The identified applications primarily rely on 3D scanning technologies, which restrict subsequent modifications of the 3D models and limit the possibility of iterative design improvements. Another significant limitation is the low level of reproducibility in a highly personalized and non standardized design approach, which prevents rapid and efficient manufacturing. The main limitations associated with the implementation of this technology highlight the need for the development of new automated and user-friendly software solutions for 3D modelling, targeting both therapists and students. Such solutions could facilitate the creation of personalized assistive devices while reducing the technological and cognitive barriers associated with their design and production.

1.4. Research Gaps and Limitations in Existing Studies

Following the literature review, several key limitations and research gaps have been identified:

- (1) The lack of established protocols for the development of interdisciplinary classes and their automation;
- (2) The presence of cognitive barriers associated with the use of new software and the limited time available for additional teacher training and professional development.

To address the first identified barrier, this dissertation develops and validates a structured and easily reproducible protocol for the design of STEAM classes integrating the three most widely adopted educational technologies.

To address the second barrier, an approach for the creation of educational materials through 3D printing is proposed. The approach is validated through the development of two experimental software programs in the AutoCAD environment, implemented using the Visual LISP programming language. The objectives of these solutions are:

- To reduce the technical complexity through automation;
- To provide educational value through the visualization of the stages involved in the 3D modelling process;
- To enable a high level of personalization through the use of individual parameters or design elements aligned with students' interests;
- To ensure that the design of objects follows the principles of minimalist and simplified design in order to increase the reproducibility, and rapid manufacturing.

The overall objective is to provide low-cost, adaptive solutions based on 3D printing that ensure high applicability and pedagogical effectiveness in educational contexts.

II. CHAPTER 2: Protocol for the implementation of an educational STEAM activity integrating 3D printing, a social robot, and an AI-based chatbot.

2.1. Development of a STEAM protocol for an educational activity.

The protocol is designed to ensure reproducibility regardless of the teacher's professional expertise, level of interdisciplinary interest, time constraints, access to existing STEAM resources and lesson design ideas, as well as proficiency in English language. The protocol is illustrated in Figure 1 and consists of the following steps:

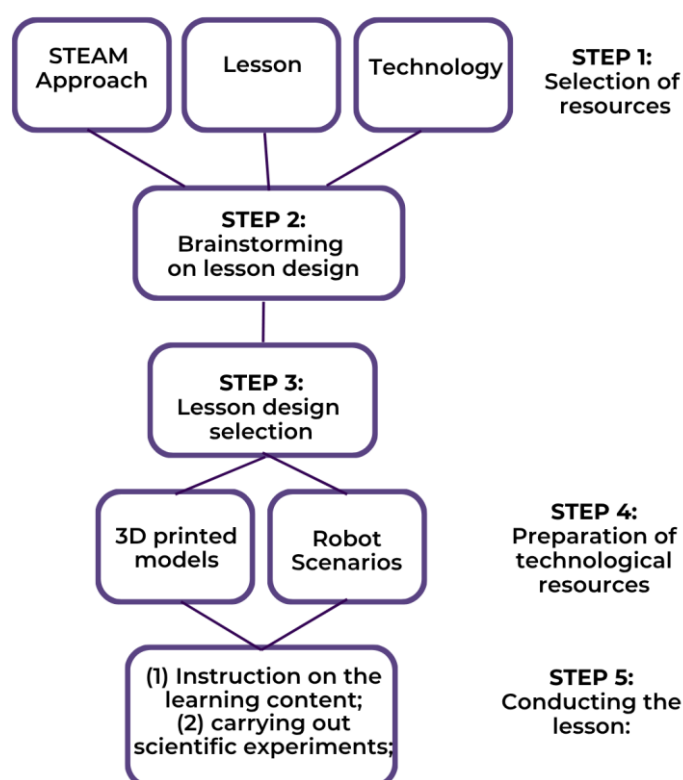


Figure 1: Block diagram of the proposed step-by-step protocol for STEAM lesson design.

Step 1 - Selection of resources (learning materials, STEAM integration of arts and technologies): This step defines the educational elements comprising the lesson and their interrelationships.

Step 2 – Brainstorming phase: This step addresses the question of how the lesson can be designed and delivered by applying the principles of STEAM education.

Step 3 – Selection of the lesson design: An analysis of the outcomes obtained in Step 2 is performed, followed by the selection of the most appropriate lesson alternative and the development of the lesson design, including opportunities for arts integration.

Step 4 – Preparation of technological tools for the STEAM lesson: This step involves the preparation of technological resources, the development of lesson scenarios, and the 3D printing of educational objects.

Step 5 – Conducting the lesson and carrying out scientific experiment, which includes administering a questionnaire and analysis of results.

2.2. Application of the developed protocol in a physics lesson on "Electrical Conductivity"

The developed STEAM protocol was implemented in a Grade 9 physics lesson at a general education school in Sofia, Bulgaria. Physics was selected as the target subject, providing an opportunity to evaluate the protocol in a learning context that presents a relatively high level of cognitive challenge for students.

Step 1: Selection of resources

- **Lesson:**

The chosen topic of the experimental lesson, entitled "Electrical Conductivity" focuses on the acquisition of new concepts, properties, and fundamental physical principles related to electrical conductivity.

- **STEAM approach**

The primary focus of the STEAM activity is physics, while art serves as a complementary pedagogical component. The interdisciplinary lesson is designed to enhance students' active participation in the learning process by increasing their engagement, fostering creative thinking related to the physics topic, and facilitating the visualization of theoretical concepts.

- **Technology**

The experiment incorporates two of the most widely adopted technologies in STEAM education: the humanoid robot NAO and 3D-printed educational models.

Step 2: Brainstorming

At the time of the experiment, in 2024, a Google search and a review of online repositories containing STEAM case studies and ready-made lesson plans revealed the absence of learning scenarios addressing the selected topic. To automate the protocol development process, Chat GPT-3.5 was employed to brainstorm lesson scenarios. This approach enabled the definition of the lesson components and the development of a detailed instructional plan. The chat bot's answers formed the basis for determining the pedagogical functions of the selected technologies and their specific implementation scenarios within the learning process.

- 3D printing technology is employed to produce personalized educational displays and instructional models.
- The humanoid robot NAO is used during the evaluation of the retained knowledge via quiz and in an informal discussion with students regarding the robot's capabilities, with the aim of increasing their interest in robotics and emerging technologies.

Стъпка 3 - Избор на дизайн на урок:

During the lesson, the students work with two 3D-printed experimental installations. The first installation is a 3D-printed model of an electrical circuit (Figure 2). The 3D-printed platform incorporates three power sources, an electrical load consisting of a direct current (DC) motor, two circuit connection boards, and a potentiometer.

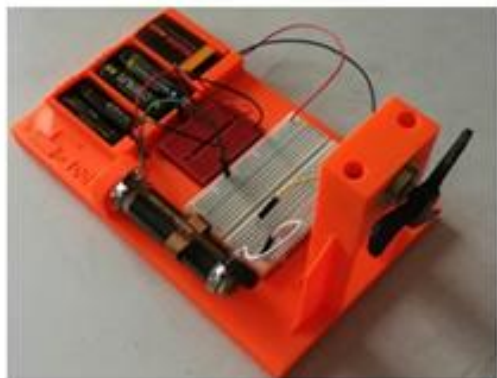


Figure 2: 3D-printed electrical circuit model developed for experimental purposes.

The 3D-printed model is designed to serve as a tool enabling students to solve practical tasks related to the lesson content.

As a creative stimulus within the learning activity, an AI-generated idea is selected involving the integration of electroluminescent and light-emitting diode (LED) elements as a means of visualizing the studied physical processes. The concept of designing the system in the form of a map of Bulgaria is developed by the research team without prompting the AI chatbot. The 3D-printed map is connected to the first experimental system (Figure II-5) and equipped with LEDs positioned at the locations of Bulgaria's major regional cities. The LEDs are activated upon the correct assembly of the electrical circuit. The map is presented in Figure 3.



Figure 3: Interactive 3D-printed map of Bulgaria equipped with LEDs positioned at major city locations.

Step 4- Preparation of Technological Resources for the STEAM Lesson

The two educational models are 3D printed. A scenario for the NAO robot is developed, enabling it to administer 11 questions to the students at the end of the lesson based on the content taught that day. The same set of questions is also used during the final stage of the

learning process, in the form of a questionnaire provided to the students. It is completed outside of class hours, with the aim of assessing the level of knowledge acquisition.

Step 5 – Implementation of the Lesson: The lesson is conducted in two parts, comprising the delivery of the instructional content and the implementation of the experimental activities.

2.3. Evaluation of the effect of the implemented STEAM protocol on student engagement among students in a traditional general education setting

The study involves behavioral observation of students' engagement throughout the three phases of the lesson, as well as a questionnaire completed by the students after the lesson. The questionnaire consisted of two parts. The first part aims to assess knowledge acquisition, while the second part is designed to record students' experiences and perceptions during the experimental class.

The results achieved by each student in the first part of the questionnaire (knowledge acquisition) are summarized and expressed as the total number of correct answers, with each correct response assigned a value of 1 point. The arithmetic mean of the results obtained by the control and experimental groups is calculated, and the resulting data is presented in Table 1.

The students from class 9A ($n = 11$) constitute the control group, while the students from class 9B represent the experimental group. Two students from 9B are excluded for null answers in the quiz. Thus, the sample size of the experimental group is $n = 21$. The physics teacher conducts the lesson with Grade 9A using a traditional teaching approach.

Table 1: Students' Results in the Knowledge Acquisition Test

Group	Mean Score	Sample Size (n)	SD (Standard Deviation)	p-value	Result / Significance
Control Group (Grade 9A)	8.00	11	2.65	0.2974	p>0.05, NS
Experimental Group (Grade 9B)	8.95	21	1.71		

The analysis of the survey data regarding knowledge acquisition indicates that the difference in mean test scores between the two groups does not reach statistical significance.

To further investigate the construct of "engagement," the various underlying attributes that constitute it are also statistically analyzed. They are registered through behavioral observation using Reeve's method [130]. The sample of this second investigation comprises the whole experimental group with a total of $n=23$ students, including those whose subsequent test responses were rendered invalid. Changes in student attitude and participation are recorded across the three phases of the lesson. The results are presented in Table 2.

For the attribute "Positive emotion," the number of students demonstrating the corresponding behavior or emotion across the three different phases of the study is recorded, representing the frequency with which this attribute was registered. Part 1 refers to the lesson

segment dedicated to traditional instruction; Part 2 involves interaction with 3D printing technology; and Part 3 describes the part with the robot NAO.

Table 2: Assessment of student engagement across each indicator. Таблица 2II: Assessment of student engagement across each indicator

	Parameters / Attributes			Mean Value and Standard Deviation			ρ - value	
	Part 1	Part 2	Part 3	Part 1	Part 2	Part 3	Part 1/ Part 2	Part 1/ Part 3
Positive emotion	2	18	21	0.09 (0.29)	0.78 (0.42)	0.91 (0.29)	0.0001	0.0001
Effort in responding to guided questions	6	14	20	0.26 (0.45)	0.61 (0.5)	0.87 (0.34)	0.0168	0.0001
Verbal participation	17	18	20	0.74 (0.45)	0.78 (0.42)	0.87 (0.34)	NS	NS
Effort in following the teacher's presentation	17	18	20	0.74 (0.45)	0.78 (0.42)	0.87 (0.34)	NS	NS
Attention	19	20	21	0.83 (0.39)	0.87 (0.34)	0.91 (0.29)	NS	NS

For the statistical analysis of these data, a paired samples t-test is applied, allowing comparison of the same subjects' indicators at different stages of the learning process. Each student demonstrating a positive attitude according to the respective indicator is assigned a score of 1, while the absence of such an attitude is assigned a score of 0. The mean values, standard deviations (SD), and ρ-values are calculated for each group and each indicator. Comparisons are performed between Part 1 and Part 2, as well as between Part 1 and Part 3..

Values without statistical significance are marked as NS (Not Significant). The study demonstrates statistically significant differences ($\rho < 0.05$) in student engagement across the different phases of the lesson for the indicators “Effort in Answering the Teacher’s Guiding Questions” and “Positive Emotion.” These findings represent a direct indicator of the positive influence of technology (in this case, the 3D printer and the humanoid robot NAO) on the quality of the educational process..

Additionally, the χ^2 test of independence and the McNemar test were applied. The analyses are based on the actual changes in students' attitudes, as presented in Table 3. A statistically significant increase is identified in the number of students demonstrating positive emotions. During the transition from Part 1 to Part 2, the results are $\chi^2 (1) = 14.06$, degrees of freedom =1, $\rho = 0.0000019$. During the transition from Part 1 to Part 3, the results are $\chi^2 (1) = 17.05$, $\rho = 0.00000002$.

For the indicator “Effort in Answering Guiding Questions” the increase in the observed positive behavior is statistically significant in Part 2: $\chi^2(1) = 6.13$, $p = 0.0173409$, $p < 0.05$. In Part 3, this increase reaches $\chi^2(1) = 12.07$, $p = 0.0000313$, as presented in Table 3.

For this indicator, the effect size observed during the pedagogical activity involving 3D printing is not as statistically pronounced. The qualitative analysis of the data reveals a distinct pattern that may explain this finding. Female students demonstrate significantly higher levels of activity and cognitive effort specifically during the activities involving 3D technologies. Since this subgroup consists of only nine students, the actual positive effect observed among female participants is partially offset.

Table 3: Chi Square and McNemar test

	χ^2 (Chi-Square)	Degrees of Freedom (df)	Significance (ρ)	
Positive emotion				
Part 1 vs. Part 2 (3D printing)	14.06	1	0.0000019	p<0.001
Part 1 vs. Part 3 (NAO robot)	17.05	1	0.00000002	p<0.001
Effort in responding to guiding questions				
Part 1 vs. Part 2 (3D printing)	6.13	1	0.0173409	p<0.05
Part 1 vs. Part 3 (NAO robot)	12.07	1	0.0000313	p<0.001

The dynamics of student engagement are observed. Particular attention is given to the behavior of students who demonstrated passive participation during the traditional part of the lesson. Their behavior shifts from passive to moderately active and active engagement during interactions with the 3D-printed educational models and the NAO robot, particularly when these activities are conducted in smaller groups. It is observed that the number of active students increases twofold during the part of the lesson assisted by the robot NAO, reaching approximately half of the total number of participants. While during the theoretical phase of the lesson (Part 1), nearly half of the sample ($n = 10$) exhibits passive behavior, the introduction of the 3D-printed model and the NAO robot increases the number of highly engaged students to 12 and 16, respectively. The results of the paired samples t-test confirms that these changes are associated with the modification of the learning environment ($p < 0.05$).

It is also observed that female students demonstrate considerable enthusiasm during the technology-enhanced presentation of the lesson. During the interaction with the 3D-printed models, the observed level of interest among female students is higher than that among male students. This finding indicates that the technology can be successfully employed as a means of overcoming apathy towards technology through creative engagement.

2.4. Conclusions from Chapter Two

A protocol for the design and implementation of interdisciplinary STEAM lessons is developed, based on the synergy between traditional teaching, 3D technologies and the humanoid robot NAO. The protocol enables process automation through the use of a generative AI-based chatbot. The effectiveness of the protocol is empirically validated through its

implementation in a real educational environment (a physics lesson), demonstrating a statistically significant increase in students' emotional and cognitive engagement. These results confirm that the integrated use of technologies in STEAM classrooms contributes to a positive student learning experience. The application of a step-by-step protocol for lesson design can serve as an effective approach for facilitating the implementation of STEAM pedagogy, regardless of the teachers' individual interdisciplinary interests and professional experience. AI-based chatbots provide opportunities for generating multiple ideas for personalization that can be implemented through 3D printing technologies and scenarios with educational robots, tailored to students' needs and interests.

Research Limitations

A significant limitation of the conducted experimental study is the small number of participants and their unequal distribution between the control and experimental groups. The homogeneity of the groups is not examined. With a larger sample size and a repeated study, these limitations could be overcome.

III. CHAPTER 3: Development of an Approach for the Automated Design of 3D-Printed Devices for Educational Purposes

3.1. Development of an Approach for the Automated Design of 3D-Printed Devices for Educational Purposes

The proposed approach is illustrated in Figure 4.

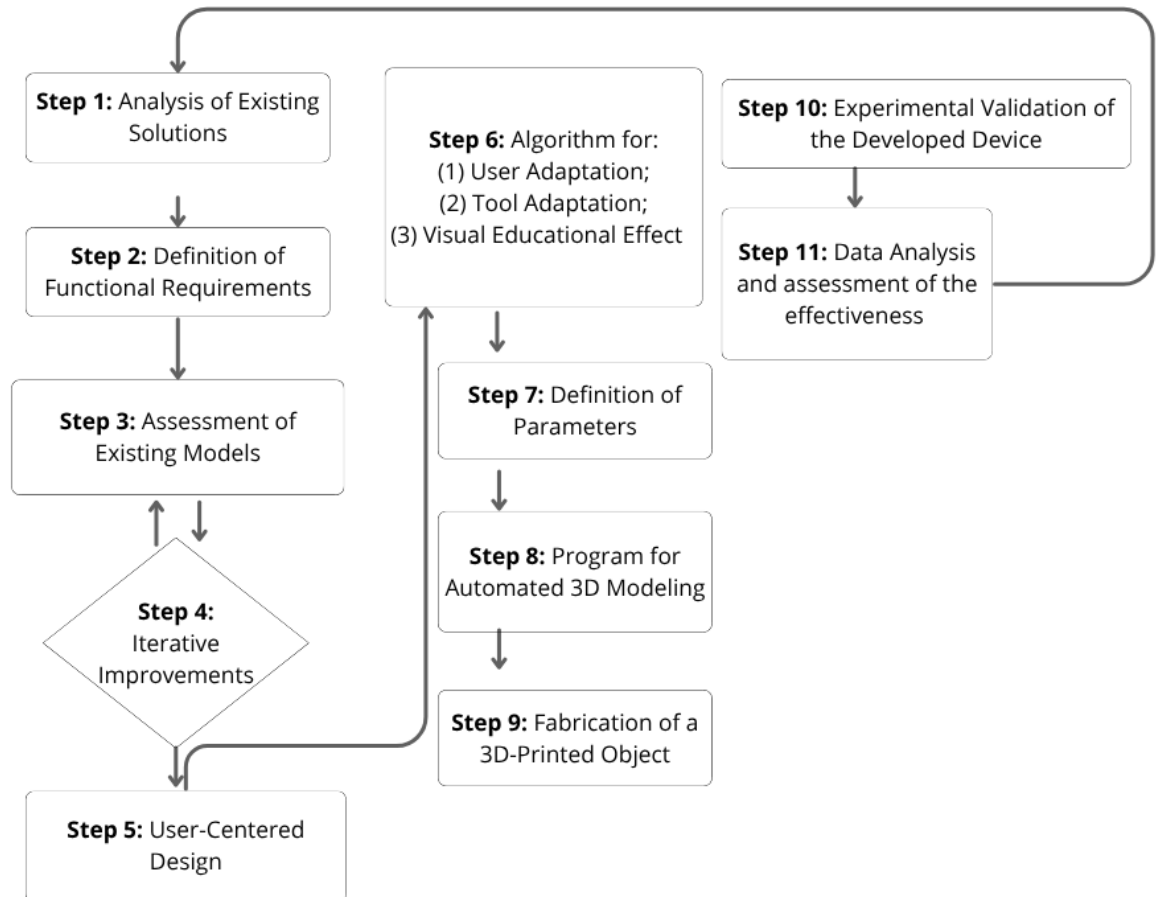


Figure 4: Step-by-Step Approach for the Design and Implementation of 3D-Printed Devices for Educational Purposes

The main steps of the proposed approach are as follows:

Step 1 – Review of existing solutions:

Based on the defined objectives and the scope of the development, existing models are searched and reviewed. The results may be obtained both through searches in academic databases and through open-access repositories for sharing .stl files, such as Thingiverse.com.

Step 2 – Definition of generic functional requirements:

The required functional characteristics that need to be satisfied are defined. This includes, for example, the identification of the relevant disciplinary field, such as applied arts, STEAM, physics, graphomotor skills development, occupational therapy, object-grasping training, and others.

Step 3 – Evaluation of existing 3D models:

Step 4 – Iterative improvements aimed at increasing effectiveness:

The initial parameters for modifying the existing concepts are recorded. A comparative analysis is performed, followed by the necessary adjustments to the input parameters.

Step 5 – Selection of a user-centered development method:

User-centered design principles are applied to enhance the effectiveness and motivation for the adoption of the device. The most appropriate interaction approach is selected, taking into account the user's cognitive and physical profile.

Step 6 – Adaptation algorithm:

The individual user parameters obtained in Step 5 are analyzed to develop the specific personalized design of the object. The development process is adapted to the user's individual needs in three main directions:

- **User adaptation (personalization):** Individual user preferences and requirements are analyzed.
- **Tool adaptation:** The specific characteristics of the educational materials, into which the 3D-printed educational aids will be integrated, are analyzed.
- **Visual and educational effect:** The users' level of technological competence is analyzed, and visualizations or informative elements are developed to stimulate their perception and motivation for continued education in the field of 3D printing.

Step 7 – Definition of parameters:

The main variables representing user-specific parameters are defined. These parameters are entered through dialog boxes. The ranges of all input parameters are established (e.g., minimum/maximum diameter, minimum/maximum angle).

Step 8 – Program for automated 3D modeling:

Based on the previous steps, a program is developed to automatically generate a 3D model within CAD software. For the purposes of this dissertation, the AutoCAD environment is used. The program generates a 3D model and an **.stl** file. The generated model can be further processed within the CAD environment, allowing additional personalization and adaptation.

Step 9 – Fabrication of a 3D-Printed educational object

Step 10 – Validation in a real educational environment

Step 11 – Qualitative/quantitative assessment of effectiveness and data analysis

3.2. Conclusions from Chapter 3

The approach developed for the purposes of this dissertation complements existing research in the field in several directions:

- It can be used to integrate automated 3D modeling at different levels of education and across various educational fields. The development aims to facilitate the process and overcome cognitive barriers related both to the physical realization of 3D-

printed educational objects and to the acquisition of skills for working with 3D modeling software.

- A higher degree of universalization is proposed through the principle of simplified and minimalist design. The approach incorporates the use of standardized basic geometry, which overcomes the limitations associated with 3D scanning technology.
- The approach proposes adaptation not only to the user but also to different tools and educational materials.

An active participant in the implementation of the proposed approach is the end user, whose individual preferences and anatomical parameters form the foundation of the developed solutions.

IV. CHAPTER 4: Development and validation of a personalized 3D modeling program for specialized artistic education

4.1. Development of the “rings” program

The process of developing and testing a program for automated 3D modeling of rings in the AutoCAD environment for the purposes of specialized artistic education is presented. The approach illustrated in Chapter 3 was applied.

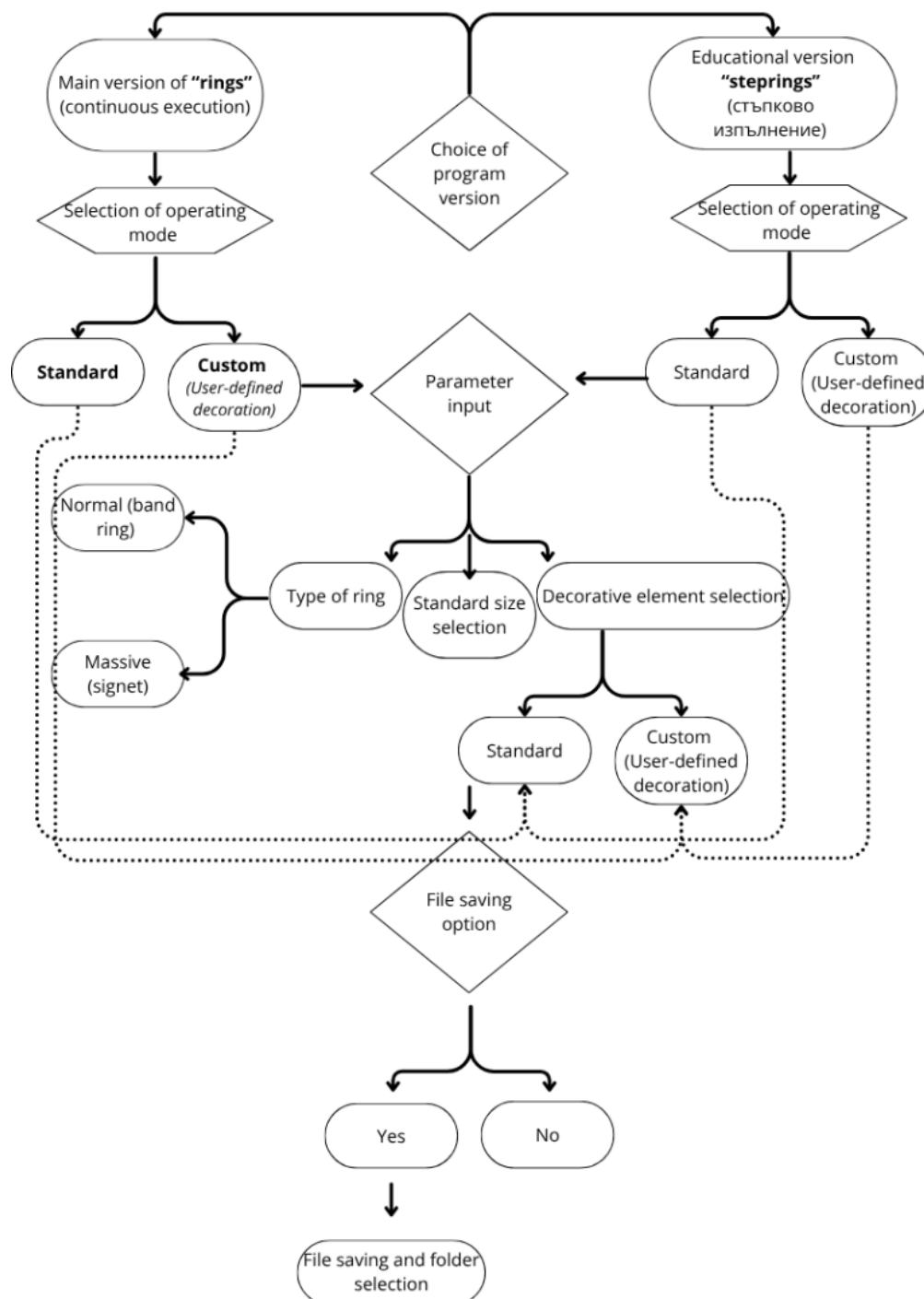


Figure 5: Flowchart of the “rings”/“steprings” program algorithm

The algorithm of the “rings” program consists of two versions: (1) the automated “rings” mode and (2) the educational “steprings” mode. Each mode has two modes: (1) “standard”, which uses predefined geometric blocks, and (2) “custom”, which allows the use of a previously created ornament in an .stl file format. The program utilizes user input provided through dialog boxes.

When the program is launched in the AutoCAD environment, the user selects which program version to access. During the standard execution of “rings”, the program proceeds through multiple steps that remain invisible to the user and generates a complete 3D model. The model combines predefined dimensions, ring types (“normal” – band ring and “massive” – signet ring) and a variety of decorative blocks. Upon this selection, a dialog box is opened, as shown in Figure 6.

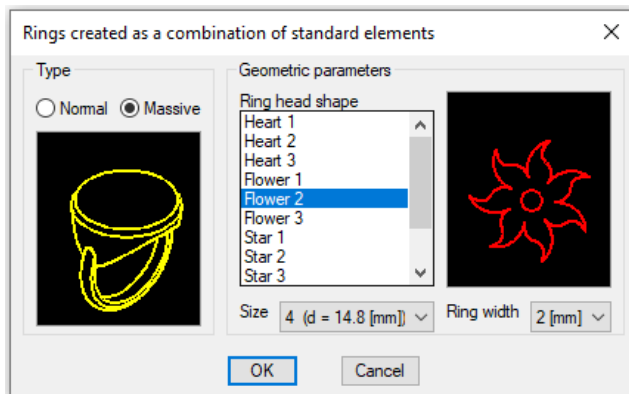


Figure 6: Dialog box for defining the type, parameters, and shape of the individual ring elements.

After pressing “OK”, the automated creation of the 3D model with the specified parameters begins.

Selecting the “custom” option opens another dialog box, shown in Figure 7, in which standard ring sizes can again be selected. However, this option also allows the user to specify a file containing a custom personalized ornament design created for the ring.

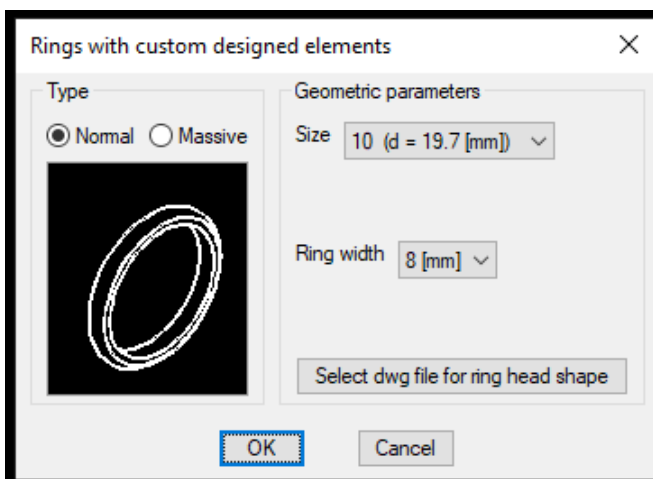


Figure 7: Dialog box for creating a ring in the “custom” version using a pre-designed .stl ornament file.

When the program is launched in the step-by-step mode (“steprings”), the execution is periodically interrupted, allowing the user to observe the processes occurring at each stage, as illustrated in Figure 8.

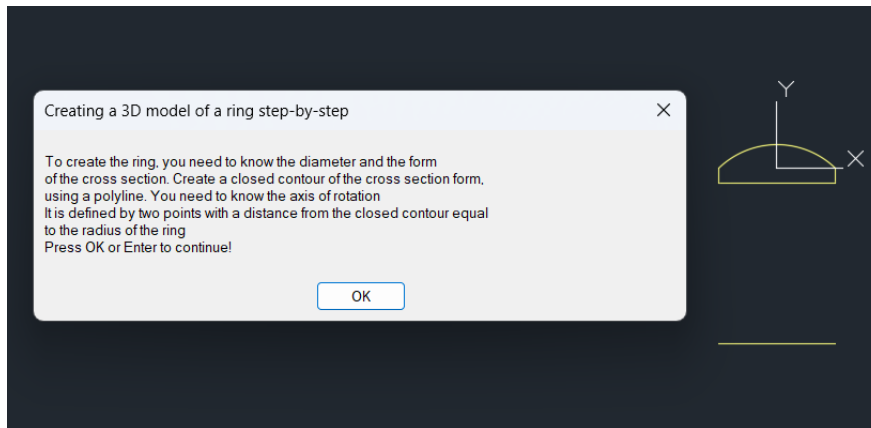


Figure 8: Educational message to the user explaining the principles of basic 3D modeling in the AutoCAD environment.

In this way, the user becomes familiar with the basic principles of 3D modeling of a ring in AutoCAD. First, the cross-section of the band ring is created. The applied geometry is illustrated in Figure 9.

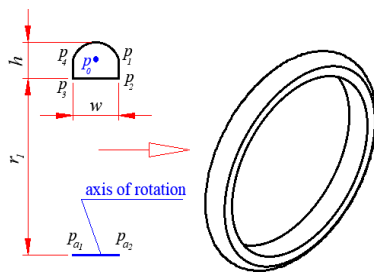


Figure 9: Basic geometry for 3D modeling of the ring band in the “rings”/“steprings” program in AutoCAD.

The coordinates of the points forming the closed contour P_1 , P_2 , P_3 , and P_4 , as well as the axis of rotation defined by points P_{a1} and P_{a2} , are calculated. The contour dimensions are determined by the parameters entered in the dialog box shown in Figure 6. The coordinates of the points are recalculated relative to a coordinate system with its origin at point P_0 . It is important that the diameter of cylinder 2 is equal to dimension d , which depends on the ring size. The parameter “ w ” represents the width of the band, while “ h ” represents the thickness, which depends on the ring size and varies between 1.5 and 2 mm. The radius $r_1 = d/2$ depends on the ring size. The distance $P_1P_2 = P_3P_4$ is a constant value (in this case, 0.8 mm), determined by the precision of the 3D printer.

Boolean operations are used to generate the solid body of the massive band ring (signet). The sequence of operations is as follows: cylinder 2 is subtracted from conical body 1 to obtain body 3, after which body 3 is combined with band ring 4.

The different modes of the “rings” program enable the user to create a 3D model while developing skills at three levels:

1. Using the program to create a ring with a selected design from the predefined library;
2. Creating a custom ornament design using a ring with standard dimensions and geometry;
3. Using the capabilities of AutoCAD to create a completely unique design.

The result of the program execution is the generation of a 3D model and an .stl file, as illustrated in Figure 10.

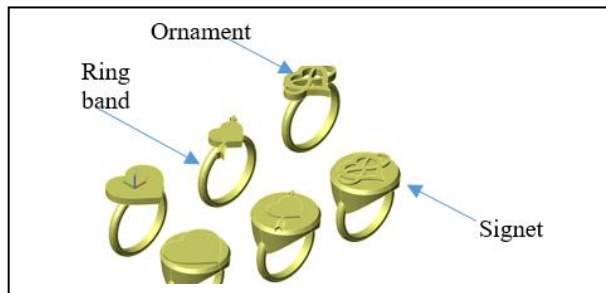


Figure 10: 3D ring models generated by the “rings” program

The “rings” program is validated both in a laboratory environment at the Institute of robotics – Bulgarian Academy of Science (IR-BAS), and in a real educational environment.

- **Functional evaluation of the “rings” program at IR-BAS**

Functional experiments were conducted to validate the quality of the rings modeled using the “rings” program.

Several criteria were considered: printing time per ring, print quality, and strength. The print quality and strength were subjectively evaluated by one person using a 5-point Likert scale questionnaire, where 0 indicates “completely unsatisfactory” and 5 indicates “excellent”. The evaluation scale for the quality of 3D printing is as follows:

- 0 – Cannot be manufactured using a 3D printer;
- 1 – Significant defects are observed when removing the ring from the 3D printer build platform;
- 2 – Rough surfaces or visible inaccuracies in the fabrication process are observed;
- 3 – Minor inaccuracies and interruptions in the ornaments are observed;
- 4 – No interruptions are present, but minor deviations from the model are still noticeable;
- 5 – The printed object corresponds exactly to the model.

The bending strength of the 3D-printed rings was also tested and evaluated by one person through repeated manual pressing with a finger applying a force of $F \approx 10$ N. The evaluation scale for the strength of the 3D-printed ring is as follows:

- 0 – The ring is damaged when removed from the 3D printer build platform;
- 1 – The band and parts of the ornaments easily break under finger pressure;
- 2 – The band deforms or breaks after repeated strong pressing;
- 3 – Only the ornaments on the ring deform or break;
- 4 – A small part of the ornaments breaks after repeated strong pressing;

5 – No visible damage to the ring is observed.

The obtained results demonstrate that the developed program is suitable for the automated generation of 3D ring models by combining linear parameters with pre-existing decorative blocks. Multiple 3D-printed rings were produced and categorized according to their complexity level and dimensions. Their properties were subsequently evaluated. Table 4 presents the results from the investigation of the quality of 3D-printed rings with a massive ornament base (signet ring type), while Table 5 presents the results for band ring-type designs.

The conducted functional evaluation confirms that the quality of 3D-printed rings decreases with increasing geometric complexity, while the strength of the band depends on its dimensions. Based on the experiments, rings with $w \geq 6$ mm are considered sufficiently strong. In Table 5, the rings generated by the program that are not suitable for FDM 3D printing technology are highlighted in yellow.

Table 4: Signet rings: printing time, quality, and strength of 3D models according to ornament complexity

Decoration	Number	Form	Printing time [min]		Quality of the 3D print		Strenght	
			w=6	w=8	w=6	w=8	w=6	w=8
Rounded	1	Heart	26	25	5	5	5	5
	2	Flower	27	26	4	4	5	5
	3	Star	27	26	5	5	5	5
Sharp	4	Heart	27	26	4	4	5	5
	5	Flower	28	27	4	4	5	5
	6	Star	28	27	5	5	5	5
Complex	7	Heart	28	27	3	3	5	5
	8	Flower	29	28	3	3	5	5
	9	Star	26	26	5	5	5	5

Table 5: Signet rings: printing time, quality, and strength of 3D models according to ornament complexity

Decoration	Number	Form	Printing time [min]		Quality of the 3D print		Strenght	
			w=6	w=8	w=6	w=8	w=6	w=8
Rounded	1	Heart	18	18	5	5	5	5
	2	Flower	20	21	4	4	4	5
	3	Star	19	20	5	5	4	5
Sharp	4	Heart	15	12	3	3	2	2
	5	Flower	21	20	3	4	3	3
	6	Star	21	21	5	5	4	5
Complex	7	Heart	17	18	3	4	3	4
	8	Flower	22	22	3	3	2	2
	9	Star	18	18	3	3	1	2

- **Investigation of the “rings” program in a real educational environment**

To implement Step 10 of the approach described in Chapter 3 and to validate the “rings” program, a scientific experiment is conducted in a vocational high school in the city of Gotse Delchev, Bulgaria, in March 2025 by a research team from IR–BAS. The study is approved by Protocol No. 10/12.03.2025 of the Ethics Committee for Scientific Research (ECSR) at IR–BAS.

An experimental group and a control group are formed from students specializing in the field of clothing design, who have practical experience in creating jewelry using various applied arts techniques.

The aim of the experiment is to investigate the effect of the independent variable—an innovative educational activity involving 3D printing—on the dependent variable: the mean value of students’ responses regarding the construct “interest in science”, measured using a five-point Likert scale questionnaire. The administered questionnaire is provided in Appendix 3 of the dissertation.

The participating students from 11th grade ($n = 21$) and 12th grade ($n = 22$) are divided into control and experimental group. The allocation of students to the two groups is performed based on statistical analysis using a t-test of their latest term grades in STEM subjects (mathematics, biology, physics, chemistry, and informatics), provided by the students through an online questionnaire included in the appendices of the full dissertation text.

The control group is shown a short film developed by the IR–BAS team presenting a jewelry-making technique known as “lost-wax casting”. The experimental group watches the same film, completed with information about the role of 3D printing in this traditional technique. After the screening, the experimental group is presented a lecture on the application of 3D printing in fashion and the production of footwear and accessories. The next stage of the experimental educational activity involved an introduction to 3D modeling in AutoCAD and practical work with the developed “rings” program.

4.2. Results from the investigation of the “rings” program in a real educational environment

The mean values reported by the two groups for each item of the “interest in science” variable before and after the educational activity, as well as the registered changes, are presented in Table 6.

Table 6: Comparative values of the elements of the “interest in science” variable before and after the innovative lesson involving 3D printing.

	Control group			Experimental group		
	Before	After	Change	Before	After	Change
Mean overall values	3,28	3,45	0,18	2,88	3,33	0,46
I can acquire knowledge and skills in STEAM disciplines.	3,71	3,44	-0,27	3,14	3,47	0,33
I can achieve a good grade in a STEAM subject.	3,90	3,67	-0,24	3,36	3,45	0,09
Strategies for acquiring STEAM knowledge.	3,29	3,06	-0,23	2,64	2,95	0,31
Knowledge in STEAM will give me an advantage in my career.	3,95	3,72	-0,23	2,77	3,35	0,58
I am confident that I can acquire STEAM knowledge.	3,71	3,50	-0,21	2,82	3,75	0,93
STEAM is connected to my life.	3,48	3,28	-0,20	4,05	3,30	-0,75
I am curious about STEAM discoveries.	3,48	3,33	-0,14	2,82	3,75	0,93
Understanding STEAM will be beneficial for my career.	3,71	3,61	-0,10	2,68	3,10	0,42
I make/have made efforts in STEAM subjects.	3,43	3,44	0,02	2,91	3,10	0,19
Studying STEAM will help me find a good job.	3,85	4,00	0,15	3,23	3,50	0,27
I want to receive an excellent grade in STEAM.	3,55	3,72	0,17	3,10	3,60	0,50
I believe that I will use STEAM problem-solving skills in my career.	3,10	3,28	0,18	2,41	2,90	0,49
I like performing better than others on STEAM tests.	3,86	4,06	0,20	3,27	3,25	-0,02
I enjoy learning STEAM.	3,19	3,39	0,20	2,82	3,90	1,08
Learning STEAM is interesting.	3,67	3,89	0,22	3,41	3,75	0,34

I prepare well for tests and laboratory exercises in STEAM disciplines.	2,95	3,22	0,27	2,45	3,05	0,60
I believe my career will be related to STEAM in some way.	2,95	3,22	0,27	2,41	3,00	0,59
It is important for me to achieve high results on STEAM tests and laboratory exercises.	3,10	3,44	0,35	3,05	3,55	0,50
I spend a lot of time studying STEAM.	2,29	2,72	0,44	2,23	3,00	0,77
I will perform well on STEAM tests.	2,71	3,22	0,51	2,59	3,20	0,61
I will perform well in STEAM laboratory exercises and projects.	2,48	3,00	0,52	2,43	3,25	0,82
I study diligently to acquire STEAM knowledge.	2,52	3,11	0,59	2,32	3,15	0,83
Acquiring STEAM knowledge makes my life more meaningful.	3,05	3,67	0,62	2,82	3,05	0,23
I believe that I can receive an excellent grade (6) in STEAM.	2,86	3,50	0,64	3,00	3,40	0,40
I think about the grade I will receive in STEAM.	3,14	3,83	0,69	3,18	3,50	0,32

The values of the “interest in science and technology” construct are obtained as the sum of the arithmetic mean values of the items presented in Table 6. The change in these values is graphically illustrated in Figure 11. A higher level of interest in science and technology after the experimental lesson is observed in both the experimental and control groups. The construct has a higher initial value in the control group; however, the increase is greater in the experimental group. This could be explained by the age and experience of the students. The control group consists of 12th-grade students. It can be concluded that an educational activity involving 3D printing and modeling, adapted to the specific interests of the class, can increase the values of the “interest in science and technology” construct even among students with lower academic achievement.

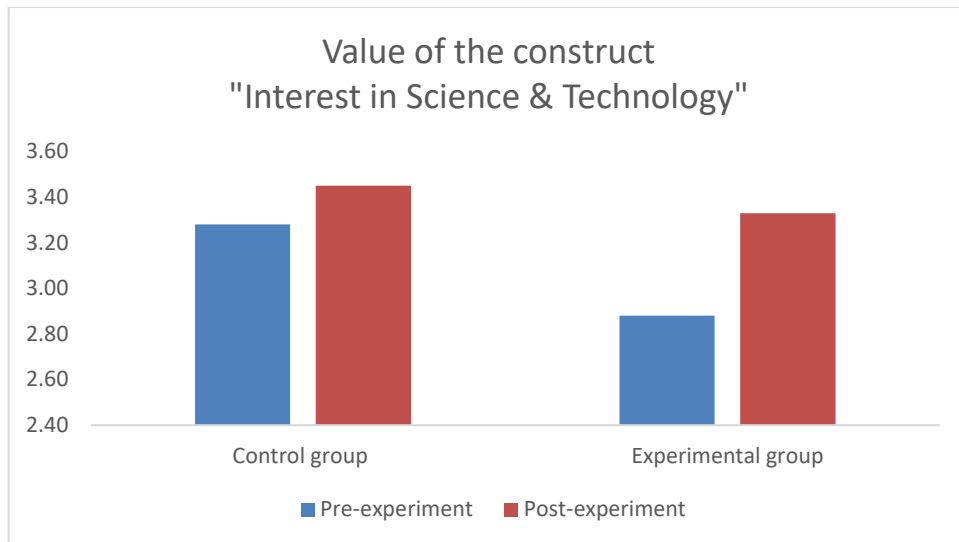


Figure 11: Value of the construct “interest in science and technology” before and after the experiment.

4.3. Conclusions from Chapter 4

An original program has been developed in the AutoCAD environment for automated and personalized 3D modeling of rings, with the capability of direct preparation for 3D printing. The program reduces the cognitive barrier associated with acquiring skills in complex CAD systems. The program is developed based on the approach described in Chapter 3. A differentiated interface with two versions is implemented: an automated version (“rings”) and an educational one (“steprings”), enabling a gradual transition from a ready-made solution to active individual design and construction. The relationship between geometric complexity, printing time, quality, and strength of the 3D models generated by the program is experimentally investigated. Through a controlled experiment conducted with a high school class specializing in arts, a positive effect of the developed software on students’ motivation and interest in science and technology disciplines is established. It can be concluded that the developed program for automated 3D ring modeling is a valuable educational resource for STEAM activities that integrate art and technology in a balanced manner.

V. CHAPTER 5: Development of a 3D-printed assistive writing device (WAD)

This chapter presents the process of creating and testing a program for personalized 3D modeling of WADs (assistive devices for writing) for students with fine motor impairments. The approach developed in Chapter 3 is applied.

5.1. Development of the program “pinky”

Step 1: Analysis of Existing Solutions

In January 2025, a survey study is conducted to investigate the effectiveness of an existing WAD1a (assistive device for writing) for students with fine motor impairments, illustrated in Figure 12. The 3D printing files of the device are provided by the user Justin Sims, a representative of Louisiana Accessible Education Materials, through the Thingiverse platform for openly shared .stl files.



Figure 12: Writing assistive device for students with fine motor impairments (WAD1a), used in a day care center for children with disabilities in Sofia for one year (March 2025 – March 2026).

The survey study is conducted using a questionnaire presented in the appendices of the full dissertation text. It is administered among 36 Bulgarian specialists working with individuals with special educational needs (SEN), including autism spectrum disorder (ASD). The participants are professionals practicing as speech therapists, psychologists, social workers, special education teachers, ICT and 3D printing experts, engineers, and researchers in this field. The study is approved by the Ethics Committee for Scientific Research (ECSR) at the Institute of Robotics – BAS, under Protocol No. 8/05.02.2025.

The analysis of the questionnaires shows that the most important element contributing to the construct of “satisfaction” with the WAD is “Meeting the needs of a person with ASD” (selected 25 times, 25%), followed by “Ease of use” with 24 selections and “Safety” with 19 selections. The device is evaluated as safer (4.58) and more durable (4.44) than effective (3.83).

Step 2: Definition of Functional Requirements

It is established that personalization according to the individual preferences of the user directly influences the effectiveness of the device. The functional requirements for such WADs,

as defined in the existing scientific literature, are investigated. These requirements include the shape and dimensions of the device, axial constraints of the grip, and individual design preferences, such as color, ornaments, texture, and the preferred writing instrument.

Step 3: Assessment of Existing Models

Based on the investigation of existing WADs and the definition of functional requirements, an evaluation of the existing WAD1a model is performed. The low effectiveness score assigned to the device is most likely due to the lack of personalization and adaptation to the individual needs of the user. The high scores for safety and durability are attributed to the minimalist design and the material used.

The relatively low effectiveness score of the device can be explained by the following factors:

- The axial constraints are not personalized and are highly likely not to match the individual grip characteristics.
- The length of the writing instrument is excessively large.

To increase the effectiveness of the device and based on the above conclusions, the need is identified for the improved writing assistive device (WAD2) to implement the following improvements:

- Increasing the extent to which the device meets the needs of individuals with SEN through personalization of the axial constraint.
- Improving the design of WAD1a by increasing its mechanical strength.
- Development and investigation of a second type of minimalist WAD1 design, referred to as WAD1b, without axial constraint.

Step 4: Iterative Improvements

WAD1a is 3D-printed at IR-BAS and provided to a day care center for working with children with SEN in order to validate its performance in a real environment and obtain additional feedback. WAD1b is functionally tested at IR-BAS by a child with left hemiparesis. The obtained feedback is based on behavioral observations and can be summarized as follows:

- WAD1a is evaluated as a convenient writing tool.
- The second axial constraint in WAD1a is not used in most cases and only the thumb constraint is applied. This observation is consistent with the results obtained both from the study conducted in the day care center and from the evaluation at IR-BAS.

When using WAD1a, two children with cerebral palsy (CP) demonstrate increased motivation to perform tasks, as well as greater accuracy and repeatability during writing activities. Based on the conducted validation, the following specific characteristics are identified:

- For the WAD1b model, due to the absence of a thumb axial constraint, manifestations of discomfort and pain in the shoulder girdle are documented. The investigations are discontinued in a timely manner, and the WAD1b design is excluded from the iteration process.

- During testing in the center for children with SEN, a structural defect is identified in the writing instrument fixation mechanism, requiring an increase in the mechanical strength of the structure.

Step 5: User-Centered Design

By applying the user-centered design approach, a new WAD, referred to as WAD2, is created with the aim of increasing effectiveness. The study is approved by the Ethics Committee for Scientific Research (ECSR) at IR-BAS under Protocol No. 1/25.03.2026. The applied geometry is based on the existing writing assistive device WAD1. The spherical shape is preserved in order to maintain the advantages of the minimalist design.

To capture the specific atypical grip of each child, a clay prototype with a shape resembling WAD1a is modeled. After the prototype is dried, the child-specific parameters are obtained using two approaches: (1) 3D scanning without additional reverse engineering and (2) manual measurement using a caliper.

Step 6: Algorithm for adaptation:

Three methods for adaptation to the user and the writing instrument are investigated: 3D scanning, manual 3D modeling in AutoCAD, and automated 3D modeling.

A pilot study is conducted with one 12-year-old participant with left-hand hemiparesis resulting from cerebral palsy (CP).

Step 7: Definition of Parameters:

The input data defined in the program are illustrated in Table 7.

Table 7: Input parameters for “pinky”, a program for automated 3D modeling of WADs in AutoCAD.

Input parameters	Purpose	Validation range / limits (mm)	Data for Participant 1 in the pilot study
Sphere diameter D	Size of the WAD	$45 < D < 85$	60
Radius R1	Axial constraint 1	$5 < R1 < 18$	12
Radius R2	Axial constraint 2	$5 < R2 < 18$	10
Distance d1	Depth of axial constraint 1	$0 < d1 < R1$	2
Distance d2	Depth of axial constraint 2	$0 < d2 < R2$	8
Angle α_1	Rotation of the cylinder with radius R1	Defined in degrees	68
Angle α_2	Rotation of the cylinder with radius R2	Defined in degrees	125
Angle α_3	Rotation of the cylinder (with radius R2) around a horizontal axis passing through the center of the sphere	Defined in degrees	-75

The basic geometric parameter of the WAD is the sphere diameter, designated in the dialog box as “Sphere diameter D”. The axial constraint for the left finger is designated as “Radius R1” and represents the radius of the cutout in which the finger is positioned. It varies within the range $5 < R1 < 18$ mm. The program creates a cylinder with radius R1, which is used to generate the axial constraint through a subtraction operation. The distance d1 defines the depth

of the axial constraint. The program allows this parameter to vary within the range $0 < d1 < R1$ mm.

The angle $\alpha1$ enables the program to rotate the cylinder (with radius $R1$) around a horizontal axis passing through the center of the sphere. All angles are defined in degrees. The angle $\alpha2$ enables the program to rotate the cylinder (with radius $R1$) around a vertical axis passing through the center of the sphere. These two angles are important because they allow the cutout to be experimentally adapted, ensuring that the device is as personalized and comfortable as possible for the user's grip.

The radius $R2$ represents the radius of the axial constraint for the right finger (i.e., the thumb of the left hand). It varies within the range $5 < R2 < 18$ mm. The program creates a cylinder with radius $R2$, which is used to generate the axial constraint. The distance $d2$ defines the depth of the cutout created by the second cylinder with radius $R2$. The program allows this parameter to vary within the range $0 < d2 < R2$ mm. The angle $\alpha3$ enables the program to rotate the cylinder (with radius $R2$) around a horizontal axis passing through the center of the sphere.

To achieve a higher degree of personalization according to the individual user's grip, the input parameters are entered into a free-text input field, allowing the user to specify exact values. If an axial constraint for only one finger is required, a minimum radius value (e.g., 0.01 mm) is assigned to deactivate the second cylinder.

Step 8: Program for Automated 3D Modeling

The “pinky” program generates WAD2 as a sphere with an opening for inserting a pen, pencil, or other writing instrument, and a flat base that facilitates layer-by-layer fabrication and attachment to the building platform. Two cylinders with radii $R1$ and $R2$ create cutouts on the sphere, representing the axial constraints for two fingers and supporting grip control and writing comfort.

The program communicates with the user through dialog boxes. The program is initiated in the AutoCAD command line by entering the function “pinky_d”. A dialog box opens, in which the user defines the input parameters, as illustrated in Figure 13.

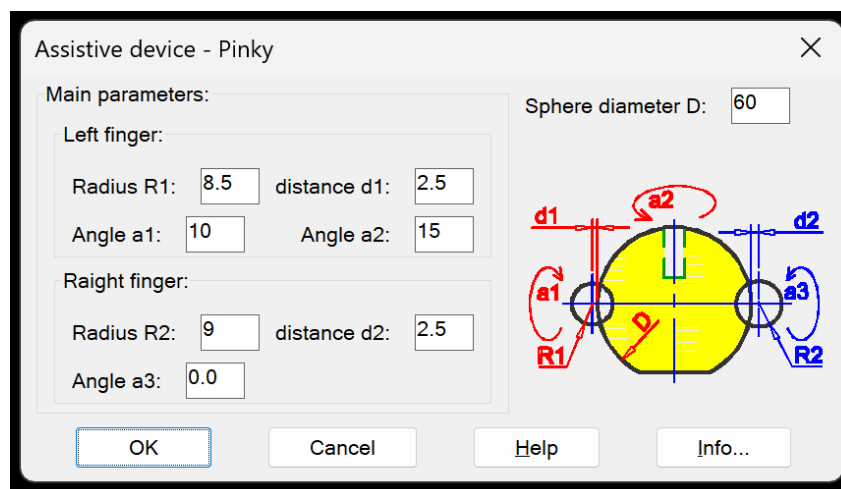


Figure 13: Input data dialog box in the “pinky_d” program

After correctly entering the required dimensions, the program proceeds to generate the required geometry. The shape and parametric dimensions are presented in Figure 14.

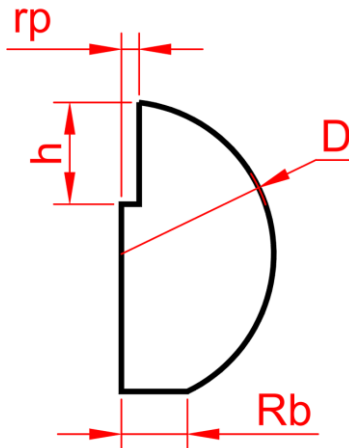


Figure 14: Basic geometry of WAD2

The parameter R_b defines the area of the base of the spherical body and is set as a constant value of $R_b = 13$ mm. It is important for manufacturing the body using a 3D printer, as it determines the contact area with the printer's build platform. The height of the opening for the writing instrument, h , is set to 20 mm. This parameter is technologically important for securing a pen, pencil, or another tool. The radius r_b is modified by the program depending on the adaptive body used for gripping the pen or writing instrument.

The main body is generated by rotating the geometry presented in Figure 13 around a vertical axis. Subsequently, the program constructs the two cylinders. The final WAD2 model generated by the “pinky” program is presented in Figure 15.

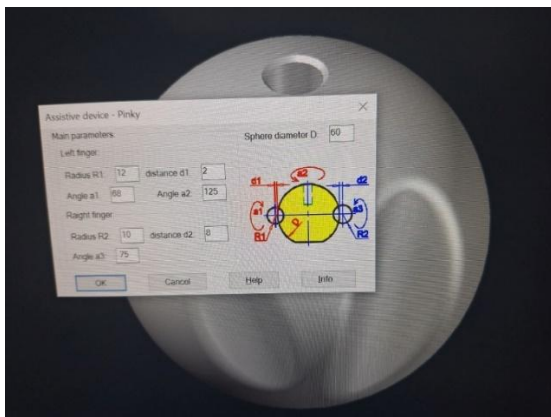


Figure 15: 3D model of WAD2 generated by the “pinky” program



Figure 16: 3D-printed model of WAD2 generated by the “pinky” program

In the final iterative improvement of the program, a new geometric block for fixing the writing instrument is incorporated to overcome the identified limitations in mechanical strength. The 3D-printed device is illustrated in Figure 16.

5.2. Conclusions from Chapter 5

A study on the effectiveness of 3D-printed WADs for students with SEN is conducted. A comparative investigation of existing methods for their creation, user personalization, and acquisition of individual dimensions is performed. The main geometric parameters that have the most significant impact on ergonomics and comfort during WAD use are identified.

An innovative design of a personalized writing assistive device (WAD2) is developed, extending existing similar devices in terms of personalization and universalization. The “pinky” program is developed for its automated 3D modeling in the AutoCAD environment. The developed program is based on the author’s approach described in Chapter 3.

The presented developments enable rapid and relatively simple 3D modeling of individualized assistive devices adapted to the specific motor characteristics of the user. This expands access to assistive technologies (AT) and creates prerequisites for such devices to be used not only by specialists but also by individuals with SEN or their families. The affordable cost of FDM 3D printers, filaments, and the possibility of using AutoCAD software free of charge by students facilitate the implementation of the “pinky” program in laboratory, school, and home environments.

Conclusion

The presented dissertation encompasses: (1) a theoretical investigation of the research domain based on the existing scientific literature, described in Chapter 1; (2) the development and experimental validation of a protocol for integrating 3D printing, AI, and robotics into contemporary STEAM education, described in Chapter 2; (3) an approach for the automated creation of 3D-printed personalized models for educational purposes, described in Chapter 3; (4) a program for automated 3D modeling in AutoCAD for the purposes of specialized artistic education, described in Chapter 4; and (5) a program for automated 3D modeling in AutoCAD for the education of students with SEN, described in Chapter 5.

Through the developed protocol and approach, significant limitations associated with the main barriers to the implementation of 3D printing technology in education and the lack of low-cost personalized assistive technologies for students with SEN are addressed.

Directions for future work

The protocol, approach, and two programs for automated 3D modeling of educational objects developed within the dissertation have significant potential for further development and application in the following directions:

1. The STEAM educational activity implementation protocol can be tested with a larger number of participants, across different disciplines, and over a longer period of time.
2. The approach for the creation and application of 3D-printed devices intended for educational purposes can be further validated through the development of automated modeling programs in CAD environments other than AutoCAD.
3. The “rings” program, described in Chapter 4, has the potential for further development through long-term quantitative and qualitative observations aimed at determining whether and how the acquired interest and motivation for working with technology and science change over time. Through behavioral observations of the process of working with the program, the specific characteristics of the creative process of art students when technology is integrated could be identified.
4. The “pinky” program provides numerous opportunities for interface improvements and the addition of new functionalities. The WADs created with the program can be integrated with other assistive devices and technologies to achieve greater effectiveness in occupational therapy for individuals with SEN.
5. The developed AutoCAD programs can be further improved through the addition of functionalities such as:
 - Additional geometric blocks enabling the automation of 3D modeling of a larger number of educational objects;
 - Saving modeled objects according to the date and user name;
 - Adding additional libraries of decorative elements and textures.

Contributions of the dissertation

Considering the results obtained from the conducted studies and presented in the dissertation, the following contributions can be formulated:

Scientific and applied contributions

1. A protocol for conducting a STEAM educational activity is developed, incorporating the use of AI to support teachers, 3D-printed educational models, and scenarios for the NAO robot. The protocol is validated during a physics lesson at the upper secondary education level in a general education school. The effect of applying the protocol on student engagement is investigated.
2. An approach for the automated creation of 3D-printed personalized models intended for educational purposes is developed. The approach includes automated generation of 3D models in the AutoCAD environment and subsequent fabrication using a 3D printer. The algorithm searches for optimal parameters in three directions: adaptation to the user, adaptation to the instrument, and visual educational effect.

Applied contributions

1. A program for automated 3D modeling of rings in the AutoCAD environment is developed. The program enables personalization of geometric parameters and automatic placement of decorative elements selected from a library. The program operates in two modes: one for generating 3D models and another that step-by-step demonstrates the model creation process for educational purposes.
2. The properties and quality characteristics of real 3D-printed models generated using the proposed program are investigated.
3. A pilot implementation of the developed software for automated creation of 3D-printed rings is conducted in a real educational process. The results are analyzed and systematized.
4. A study on the effectiveness of 3D-printed writing assistive devices (WADs) for students with SEN is conducted. Different approaches for creating personalized assistive devices are analyzed. Methods for adaptation and acquisition of individual dimensions are investigated. Based on this analysis, the main geometric parameters that have the most significant impact on ergonomics and comfort during use are identified.
5. A program for automated creation of a 3D model of a personalized writing assistive device for students with fine motor difficulties is developed.

List of Scientific Publications

The main results of the dissertation are published in scientific literature during the period 2023 – 2026, and are as follows:

Kostova, B., Georgieva-Tsaneva, G., Chavdarov, I. and Kostova, S., 2025, April. Exploring 3D Printing as an Assistive Technology for Learners with Autism Spectrum Disorder: A Comprehensive Review and Analysis of Scientific Studies. In International Conference on Digital Transformation in Education and Artificial Intelligence Application (pp. 27-51). Cham: Springer Nature Switzerland, SJR 0.182, Q3 https://doi.org/10.1007/978-3-032-02801-3_3.

Chavdarov, I., **Kostova, B.** and Georgieva-Tsaneva, G., 2024, September. Application Development in AutoCAD Environment for Modeling 3D Printed Souvenirs Targeting STEAM Education. In 2024 International Conference on Software, Telecommunications and Computer Networks (SoftCOM) (pp. 1-6), IEEE, <https://doi.org/10.23919/SoftCOM62040.2024.10721881>.

Kostova, B., Chavdarov, I., Georgieva-Tsaneva, G., Kostova, S. and Krastev, A., 2024, September. Integrating Creativity in a STEAM Physics Lesson by using 3D Printing and a Humanoid Robot NAO. In 2024 International Conference on Software, Telecommunications and Computer Networks (SoftCOM) (pp. 1-6). IEEE, <https://doi.org/10.23919/SoftCOM62040.2024.10721693>.

Kostova, B., 2025. Increasing science and technology motivation in fashion students through educational activities with 3D printing. Science Series-Innovative STEM Education, STEM Edu conference, Bulgaria, ISSN:2683-1333, 38; DOI: <https://doi.org/10.55630/STEM.2025.0738>

Identified Citations

Two citations have been identified for publication: Kostova, B., Chavdarov, I., Georgieva-Tsaneva, G., Kostova, S. and Krastev, A., 2024, September. Integrating Creativity in a STEAM Physics Lesson by using 3D Printing and a Humanoid Robot NAO. In 2024 International Conference on Software, Telecommunications and Computer Networks (SoftCOM) (pp. 1-6). IEEE.

[1] Ordoumpozanis, K., Konstantakis, M., Zoi, S. and Caridakis, G., 2025, September. Generative AI: A Systematic Review of Related Interfaces and Interactions. In Proceedings of the 3rd International Conference of the ACM Greek SIGCHI Chapter (pp. 39-47).

[2] Guvendiren, M., 2026. Implementing 3D Printing in Engineering Education: Development and Assessment of an Integrated Lecture–Laboratory Course.

Three citations have been identified for publication: Chavdarov, I., Kostova, B. and Georgieva-Tsaneva, G., 2024, September. Application Development in AutoCAD Environment for Modeling 3D Printed Souvenirs Targeting STEAM Education. In 2024 International Conference on Software, Telecommunications and Computer Networks (SoftCOM) (pp. 1-6). IEEE;

[1] Chehlarova, N., Chehlarova, K. and Gecheva, N., 2025. STEAM Workshops with a 3D Pen. ПЕДАГОГИЧЕСКИ ФОРУМ Учре-дители: Trakia University, 13(1), pp.41-49.

[2] Chehlarova, N., 2025. 3D Printed Educational Resources for Studying Percentages by People with Visual Impairments. Пе-дагогически форум, (2), pp.97-106.

[3] Chehlarova, N., Chehlarova, K. and Gecheva, N., 2025. Application of 3D Printing in the Study of Quadrilaterals in 5th Grade. Science Series-Innovative STEM Education, 7, pp.152-157.

One citation have been identified for publication: Kostova, B., 2024. The Use of 3D Printing Technology in Education for Students with Autism Spectrum Disorder–Assessment of Good Practices. Science Series-Innovative STEM Education, 6, pp.173-181.

- Chehlarova, N., Chehlarova, K. and Gecheva, N., 2025. Application of 3D Printing in the Study of Quadrilaterals in 5th Grade. Science Series-Innovative STEM Education, 7, pp.152-157.

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Summary

The domain of this dissertation is the use of modern technologies for educational purposes. The study focuses on the application of 3D printing, alongside robotics, and AI (AI), in three main areas of education: traditional education, specialized education in Arts and Humanities, and for students with Special Educational Needs (SEN).

The subject of the research includes:

1. A protocol representing a methodological framework for conducting a STEAM educational activity that incorporates AI-assisted teacher support, 3D-printed educational models, and educational scenarios implemented through the NAO robot;
2. An approach for the creation of personalized 3D-printed models intended for educational purposes. The approach involves the automated generation of 3D models within the AutoCAD environment, followed by their fabrication using a 3D printer. The underlying algorithm searches for optimal parameters in three dimensions: (1) user adaptation, (2) tool adaptation, and (3) visual effect with educational value;
3. A software application for the automated 3D modeling of rings within the AutoCAD environment;
4. An investigation of the effectiveness of an existing 3D-printed assistive writing device designed for students with SEN;
5. A software application for the automated generation of a 3D model of a personalized writing aid intended for students experiencing difficulties with fine motor skills.