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Article

Multi-Material 3D-Printing Nozzle Design Based on the Theory of Inventive Problem Solving and Knowledge Graph

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Abstract: Fused deposition modeling (FDM) technology is an emerging technology with promising applications, with the nozzle playing a crucial role in extrusion, heating, and material ejection. However, most current extrusion-based 3D printers handle only single-material printing, making the integration of multiple materials through a single nozzle challenging due to compromised quality and clogging risks. This paper introduces a method to design multi-material 3D printing nozzles using the Theory of Inventive Problem Solving (TRIZ) and knowledge graph (KG). By optimizing design and leveraging TRIZ's contradiction resolution principle, this study addressed bottlenecks and complexities in multi-material nozzle design, providing insightful recommendations. A patent knowledge graph focused on spray nozzles was created, storing material properties, design elements, and constraints for enhanced knowledge sharing. Building on identified challenges and recommendations, the study utilized keyword searches and associative paths in the knowledge graph to guide designers in generating innovative solutions. Validation was achieved through two distinct nozzle design models resulting from guided innovations. The TRIZ-KG methodology presented in this paper provides designers with a systematic cognitive framework to empower designers in overcoming technical obstacles and proposing precise solutions.

Keywords: multi-material 3D-printing nozzle; Theory of Inventive Problem Solving (TRIZ); knowledge graph (KG); inventive principle; nondestructive testing; structural health monitoring

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1. Introduction

Fused-deposition-molding 3D-printing technology finds widespread application in polymer molding [1–3]. The nozzle, a pivotal component of the fused-deposition-molding printing apparatus, necessitates a design that effectively accommodates the demands of conversion, mixing, flow, and curing among diverse materials [4]. Furthermore, it must consider variables such as material viscosity, melt temperature, rheology, and shrinkage during the curing process [5,6]. Having grasped the unique prerequisites of nozzle design, this study employed the analytical model and solution tools within TRIZ-KG to proffer precise solutions to the distinct challenges of nozzle design. Two design solutions, aligned with the stipulated design criteria, were subsequently formulated.

A systematic innovation design approach known as TRIZ was originally formulated by G. Altshuller [7]. TRIZ offers solution tools such as the ideal final result, substance-field analysis, conflict matrix, and inventive principles. These tools empower individuals to resolve challenges more efficiently and conceive of highly creative products. Bai et al. expanded upon TRIZ with a multi-contradiction resolution technique for conceptual design, pinpointing crucial contradictions and applying necessary inventive principles [8]. Hu et al. integrated TRIZ with a novel human intelligence technology, CBR (Case-Based

Reasoning), leveraging TRIZ as the foundation for database retrieval [9]. In a different vein, YamaShina et al. harmonized QFD (Quality Function Deployment) and TRIZ methodologies during new product development, systematically amalgamating the two for technological innovation via the product innovation development process [10]. M. Ogot explored the symbiotic link between axiomatic design and TRIZ in conceptual design. Upon unearthing physical contradictions, the axiomatic independence principle guides the selection of appropriate standard solutions [11]. Collectively, these studies underline TRIZ's potential to surmount technological barriers. Simultaneously, multi-material 4D printing establishes the groundwork for a new era in soft robotics technology. The utilization of rigid planar parallel robot manipulators is also profoundly significant, given their numerous favorable attributes, as determined through multiphysics analyses [12,13]. In this study, multi-material 3D-printing technology was used to print the designed nozzle model into a structure with an adjustable bending ability, and the required shape change can be guaranteed by the process parameters.

To harness TRIZ's full potential in product design, it necessitates integration with other theories based on distinct design requisites to maximize its benefits. The inventive principles in TRIZ are abstract, often necessitating designers to draw upon their own experiences to conjure innovative solutions. Knowledge can augment designers' capacity to generate design inspiration within the TRIZ framework [14–16]. Knowledge graphs emerge as effective tools to organize and visually present information, bolstering efficient and intelligent applications [17–19]. L. Guo et al., for instance, harnessed knowledge graph technology to structure process knowledge and equipment resources, resulting in an efficient process reasoning system that substantially reduces superfluous labor for process personnel [20]. In a similar vein, Zhu et al. constructed pertinent knowledge graphs, interweaving them with FBS and other production design strategies, a validation supported by case studies [21,22]. While numerous knowledge graphs have been developed within specific fields, their fusion with innovation principles remains relatively unexplored. Establishing knowledge graphs that seamlessly integrate TRIZ theory and then implementing them into the product design process remain a challenge yet to be fully met.

Printing failures, low process reliability, and challenges in controlling the FDM printing process significantly impact the quality of printed components, leading to wastage of both time and resources. Analyzing error-inducing parameters through in situ sensing and monitoring is crucial to mitigate these effects. To ensure print quality, an innovative approach involves designing an optimal FDM 3D-printing nozzle. This approach incorporates in-process monitoring, diagnosis, and feedback-based strategies to enhance print quality, addressing issues such as nozzle-clogging errors, poor spitting, defects, anomalous behaviors, and quality uncertainties [23–27].

This paper introduces a design process model based on the Theory of Inventive Problem Solving–knowledge graph (TRIZ-KG). The model employs TRIZ's conflict matrix and inventive principles to identify design problems, suggest improvement directions, and propose design solutions. Leveraging patent data in the engineering field, a patent knowledge graph was constructed. The graph enables the design-knowledge exploration through keywords and interconnected pathways. Utilizing the Neo4j graph database tool(Neo4j GmbH, headquartered in Stockholm, Sweden), design knowledge is visually represented, aiding intuitive searches and knowledge dissemination. This approach guides designers in generating innovative solutions. Ultimately, a two-nozzle model was developed based on the innovative scheme, validating the feasibility of the proposed model and method.

2. Design Methodology

2.1. TRIZ Problem-Solving Direction Capture

This paper identifies issues within the product system and proposes design suggestions utilizing TRIZ's conflict matrix and 40 inventive principles. Subsequently, the knowledge graph is employed to locate problem-solving solutions based on the proposed suggestions. This culminates in the generation of multiple product schemes by amalgamating inventive principles with an understanding of the functional semantic SVOP [28] and the design knowledge graph. Interpreting the 40 inventive principles through the lens of semantic SVOP enhances designers' comprehension of measures and solution seeking. However, at this juncture, the depiction of functions and measures remains considerably abstract, thus necessitating further assistance. To this end, the term "problem-solving direction" is introduced: a recommended path for addressing issues, formulated through the mapping of inventive principles and denoted as Q(n) (n = 1, 2, . . .). Within the design-solution generation process, TRIZ's tools are harnessed to identify encountered issues, consequently unearthing problems within the product system. From these tools, inventive principles capable of inspiring design solutions are derived, subsequently leading to suggestions for problem-solving directions.

2.2. Establishment of Knowledge Graph

The knowledge graph discussed in this article was built based on the research content of the research group [29,30] and the dataset publicly available from L. Siddharth et al. [31]. The patent claims were processed by L. Siddharth, and triplets of <entity, relationship, entity> were extracted from each patent to form the knowledge of a single patent. To prevent duplicate nodes from appearing in the graph database, entity deduplication was performed on both the head and tail parts of the triplets before importing them into Neo4j. This simplified the later graph generation and visualization operations, eliminated duplicate nodes with the same name, enhanced the links between nodes, and stimulated the design through the relationships between phrases.

Through these steps, we obtained the text data of the knowledge triad, and these data were then saved and output as CSV files in the form of "entity–relationship–entity". We then batch imported them into Neo4j (Graphical Database Tools) desktop for knowledge storage and implemented the knowledge storage and visualization in Figure 1, based on Neo4j.

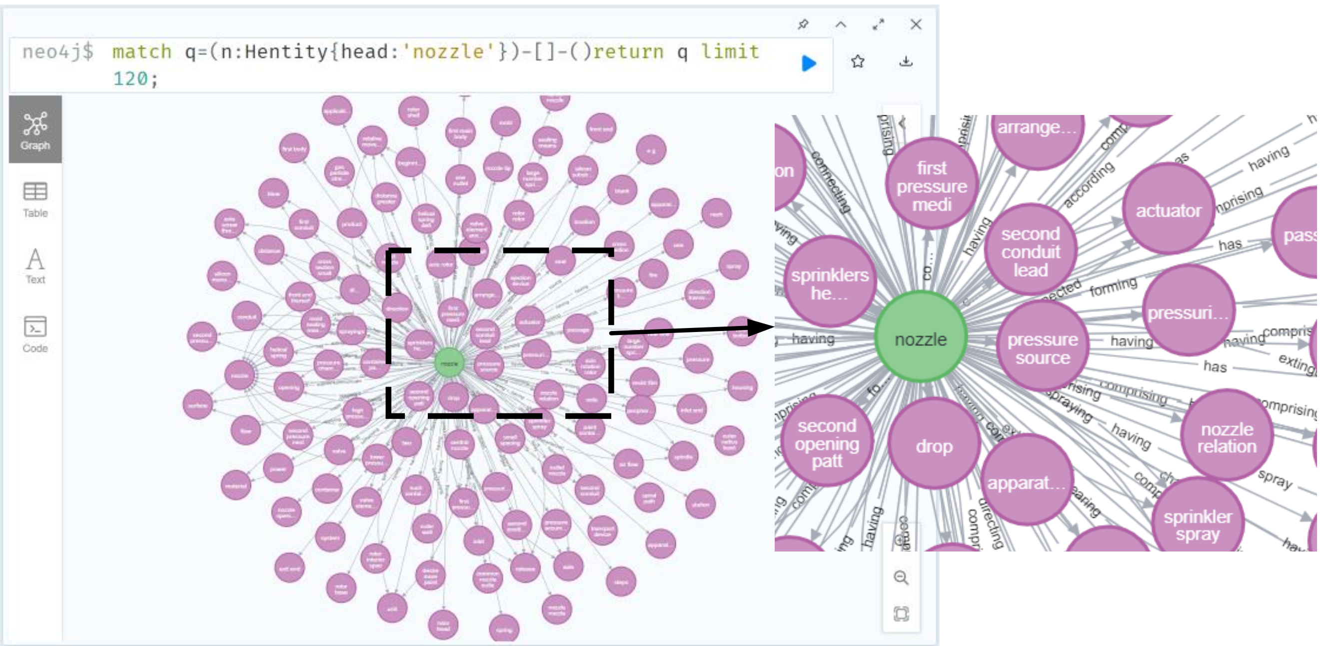


Figure 1. Neo4j-based knowledge storage and visualization.

2.3. Knowledge Visualization Search Based on KG Path

The visualization of and search for design knowledge were built based on the constructed knowledge graph. The extended retrieval model of design knowledge based on the knowledge graph allows us to obtain triad knowledge, most of which comes from the first- and second-order neighbors of the retrieval entity and its extended entity. When targeting one of the more important pieces of knowledge, we can take advantage of the knowledge graph visualization and use path tracing in the graph to obtain knowledge. As shown in Figure 2, When searching for design knowledge, designers can search for design knowledge based on the entity according to their design needs, and for useful design knowledge, they can continue to search according to the relationship path to obtain sufficient knowledge stimulation and generate multiple design schemes. Neo4j provides users with a visualization interface that allows for path-expansion operations directly on the knowledge graph. In Figure 2, with node $Dn1$ as the center, the first-level relational nodes (first-order neighbors of entities) are traced, and after continuous expansion, from $Dn1$ according to the path route = {$Dn1$, $Dn2$, $Dn3$, $Dn4$}, the node $Dn4$ can be searched, and each node will be connected by some path. Generally, the closer the paths between the nodes, the closer their relationships, and the easier they are to discover; while some relationships are not easy to discover between nodes that are far apart, these relationships can stimulate design and generate innovative ideas.

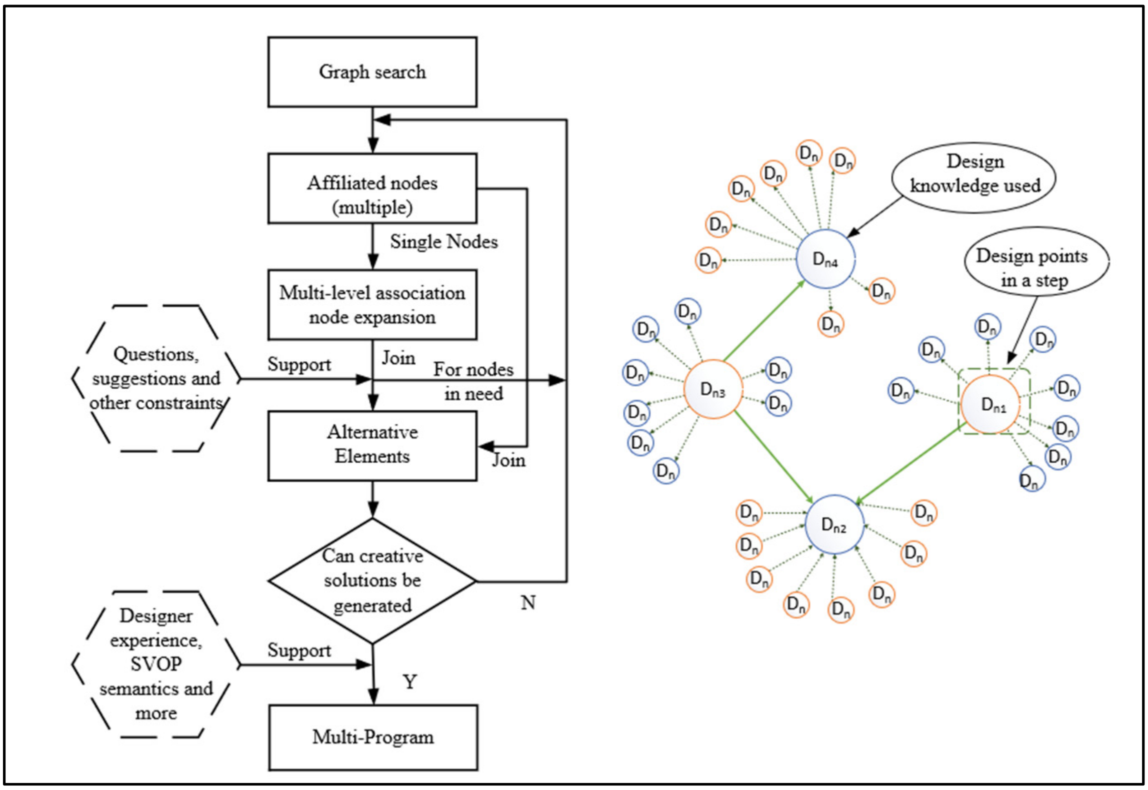


Figure 2. Design knowledge visualization process and schematic diagram.

Take the design of the nozzle as an example. When designing a spray nozzle, we first apply some classic and commonly used design methods, such as TRIZ. However, when it comes to steps such as "inventive principle", "separation principle", and "standard solutions", it is still in a relatively abstract stage, and more specific ideas, structures, functions, etc., may be needed to guide and assist the design process. As shown in Figure 3, we can visually search and filter through the paths in the graph. Neo4j supports mouse operations directly on nodes in the visualization interface, such as deleting nodes or displaying next-level relationships; only a partial set of nodes is shown in Figure 3. Starting from "nozzle" and through a certain path search, the knowledge of "having to rotate, separate, and enter devices" is obtained.

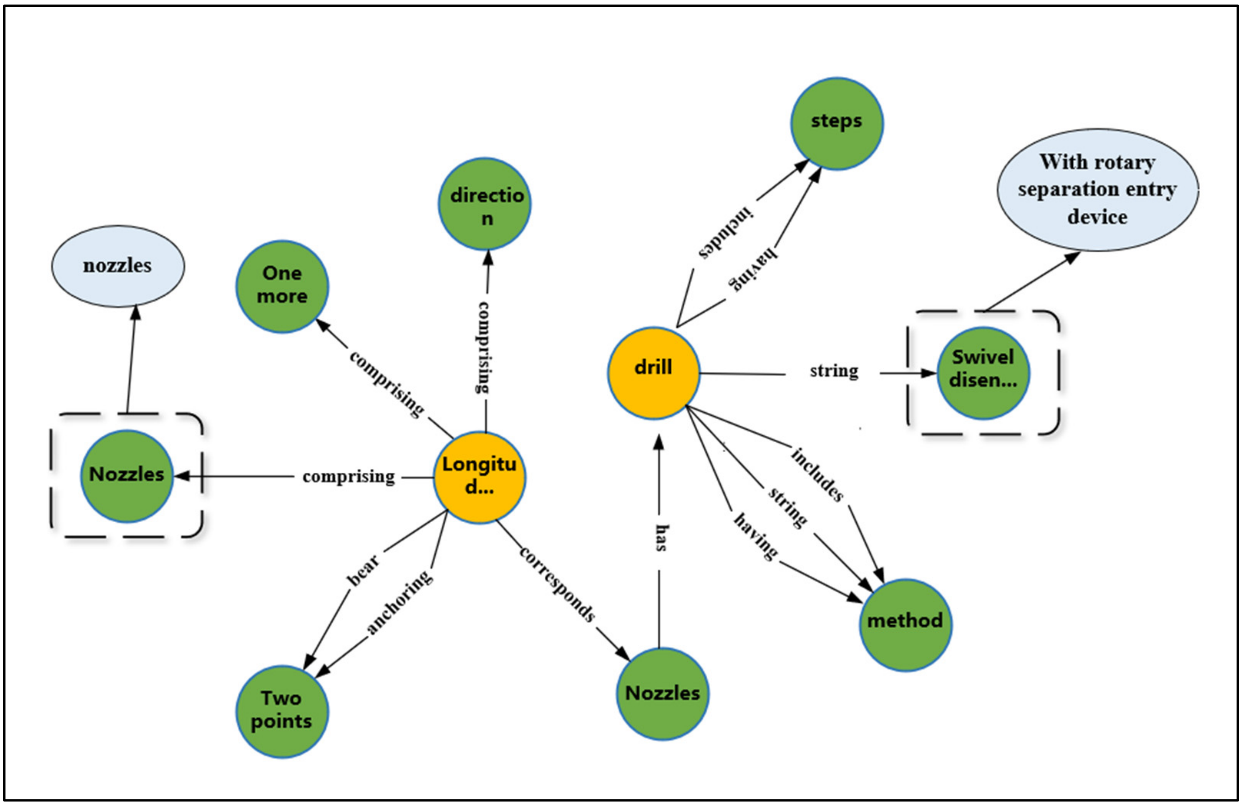


Figure 3. Design knowledge visualization search example display.

2.4. Design Solution Generation

The product-solution-generation process is illustrated in Figure 4. In the initial stage, the design requirements for the product might be vague and uncertain, often lacking comprehensive function descriptions that facilitate the formulation of design solutions. To initiate the process, the product's systemic contradiction is correlated with the TRIZ contradiction. Subsequently, the conflict matrix is consulted to identify and select the relevant inventive principle. This selected inventive principle, coupled with the product system, serves as the basis for proposing a preliminary scheme design, offering an initial direction for conceptual design. Next, adhering to the design requirements, a search is conducted within the knowledge graph to acquire pertinent design knowledge. Beginning from a specific node, the search expands to its related nodes and relationships. By incorporating the product system and the suggested problem or recommendation, necessary nodes and relationships are incorporated into the alternative design knowledge database. For critical nodes, further correlation searches at the subsequent level can be performed, enabling the retrieval of essential design knowledge along established paths. Once a substantial amount of design knowledge is amassed within the alternative design knowledge repository, conducive to generating multiple product schemes, the mapping search process is concluded. Ultimately, creative concepts are generated by merging the acquired design knowledge from the knowledge graph with functional semantics SVOP, comprehending the recommended inventive principle. This culminates in the creation of numerous solutions, encompassing diverse inspection and monitoring approaches [27], while striving for a harmonious balance between them.

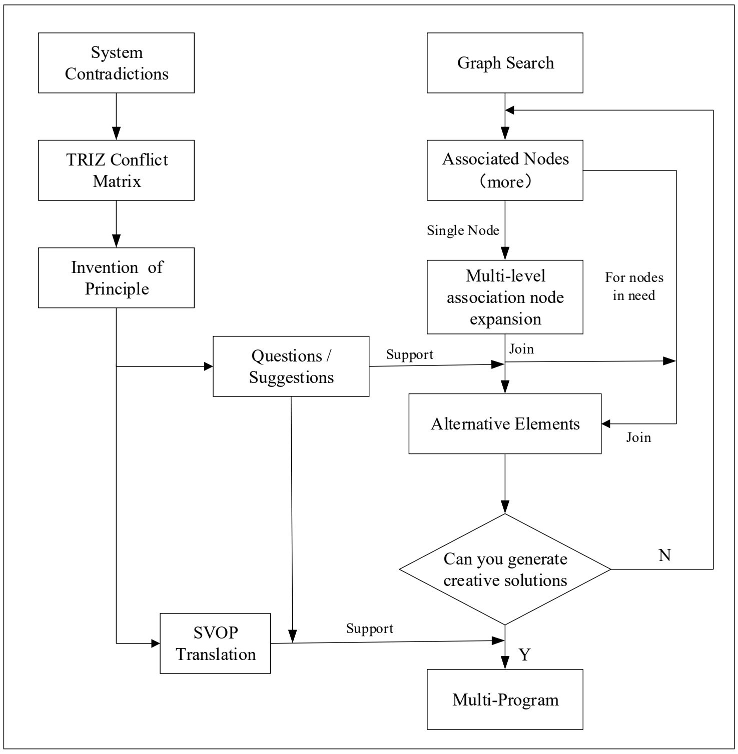


Figure 4. Flowchart of design solution generation.

3. Case Study

With the rise in demand for multicolor and multi-material printing, certain 3D-printing devices have been developed to incorporate dual or multiple nozzles. However, most of the current extrusion-based 3D-printing devices are limited to single consumable printing. Attempting to use multiple materials within a single nozzle often leads to problems such as inadequate material deposition and frequent clogging [32,33]. Moreover, replacing nozzles during the printing process proves challenging, as it compromises positional accuracy and subsequently affects print quality. This necessitates material characterization, defect inspection, and geometric measurements.

In essence, these challenges can be grouped into the following three key issues:

- Multi-material printing is not possible due to poor spitting caused by insufficient extrusion strength of the consumables.
- Blockage problem caused by uneven temperature heating.
- The 3D-printing device cannot perform the printing in situ.

3.1. FDM 3D-Printing Mechanical Device

The FDM 3D-printing device comprises a nozzle body, nozzle, feeding device, heating device, melting chamber, extrusion device, discharge tube, stepper motor, temperature sensor, and more [34,35]. Considering the system composition and operational principles of the FDM 3D-printing device, it can be categorized into three main sections:

- Fixed and non-removable physical parts, including the nozzle body, feeding device, extrusion device, feeding tube, nozzle, etc. These parts are all modules that cannot be disassembled or physically changed during the printing process.
- Removable parts, such as the heating device. The operator can adjust the temperature by disassembling and modifying it to meet the different temperature requirements of different consumables.
- Control and detection section, including the stepper motor, temperature sensor, guide rail, etc. These parts can provide working data during operation and adjust the extrusion speed of the nozzle by adjusting its speed, making it a controllable part

for the operator during use. Different nondestructive testing and monitoring can be considered for the specific design and functionality.

For each stage of rough component selection and design, the design choices for the stepper motor, feeding device, extrusion device, etc., do not impact the final functionality of the in situ multi-consumable 3D-printing nozzle. Therefore, conventional motors, roller-based feeding devices, and gear-tightened extrusion devices can be chosen. The mechanical aspects of the 3D-printing device are illustrated in Figure 5.

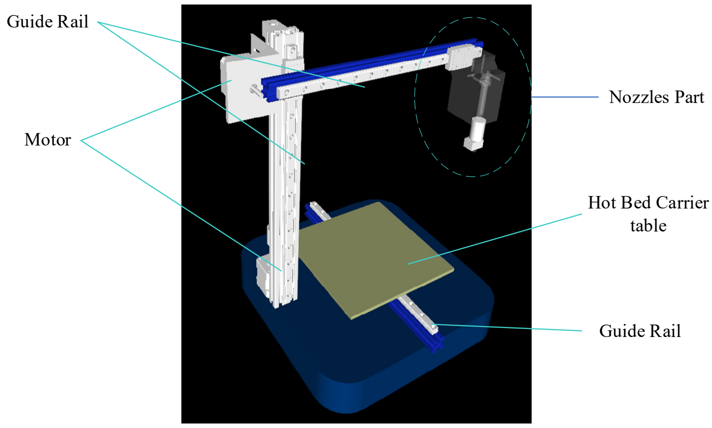


Figure 5. FDM 3D-printing mechanical device.

The nozzle section encompasses components such as the nozzle itself, heating block, throat, feeding mechanism, and other relevant parts. Throughout the printing process, the feeding mechanism directs the consumables into the throat channel. The heating block envelops the lower segment of the throat, with the nozzle attached beneath it. As the materials are subjected to heat, they progressively liquefy within the lower section of the throat channel. This process engenders an interaction between unmelted and molten materials within the channel, resulting in a piston effect. This effect propels the semifluid material out of the nozzle, depositing it onto the desktop or onto the existing upper layers.

3.2. Problem Identification and Recommendation Formulation

3.2.1. System Contradiction

The prevailing issues, requirements, and context pertaining to the nozzle are translated into relevant system contradictions during the design phase, leveraging the designer's experience in the process.

- Use of multiple consumables can lead to clogging;
- Use of multiple consumables can lead to contamination;
- Multiple nozzle replacements can be time-consuming and can affect printing accuracy.

3.2.2. Conflict Matrix

In multi-material printing, using multiple colors and materials with the same nozzle may cause contamination and nozzle clogging [36]. According to the contradictory parameters of the system at the time of 3D-printing nozzle design, this technical contradiction corresponded to the TRIZ conflict matrix, and the parameter that was improved was the "number of substances or things" (corresponding to engineering parameter No. 26), which affected the "stability" (corresponding to engineering parameter No. 13) and "reliability" (corresponding to engineering parameter No. 27) of the system (corresponding to engineering parameter No. 13) and "reliability" (corresponding to engineering parameter No. 27), while deteriorating the parameter "harmful factors generated by the object" (corresponding to engineering parameter No. 31).

3.2.3. Inventive Principle

According to the contradiction between "quantity of matter or thing" and "stability", we find the matrix and obtain inventive principles No. 15, dynamics; No. 2, extraction; No. 17, multidimensionality; and No. 40, composite material.

According to the contradiction between "quantity of matter or thing" and "reliability", the matrix is searched, and inventive principles No. 18, mechanical vibration; No. 3, local mass; No. 28, substitution of mechanical systems; and No. 40, composite materials, are obtained.

According to the contradiction between "the quantity of the substance or thing" and "the harmful factors produced by the object", searching the matrix, we obtain inventive principles No. 3, local mass; No., 35 change of physical or chemical parameters; No. 40, composite materials; and No. 39, inert environment.

3.2.4. Selection Principle

Principle No. 15 and principle No. 17 are more adequate according to the contradiction between "quantity of substances or things" and "stability" and the interpretation of the inventive principle.

According to the contradiction between "quantity of substances or things" and "reliability", principle No. 3 is more adequate in combination with the interpretation of the inventive principle, and the problem statement or recommendation statement is defined according to principle No. 3: the system should be designed to be as localized as possible (so that the object performs its function optimally).

Principle No. 3 and principle No. 39 are more adequate according to the contradiction between the "quantity of the substance or thing" and the "harmful factor produced by the object", combined with the interpretation of the inventive principle. The problem statement or recommendation is defined according to principle No. 3, which states that the system design should be localized as much as possible (so that the objects perform their respective functions optimally); and according to principle No. 39, which states that the problem statement or recommendation should be defined—the vacuum environment can be considered.

3.2.5. Questions/Suggestions

The contradiction between "quantity of matter or things" and "stability" is defined by the problem statement or recommendation according to principle No. 15, the system should be designed as dynamically as possible (even if the system is more flexible), and the problem statement or recommendation according to principle No. 17. Suggested statement: The spatial variation of objects should be considered.

The contradiction between "quantity of substances or things" and "reliability" is defined in principle No. 3, which defines the problem statement or recommendation statement: the system should be designed to be as localized as possible (so that the objects perform their respective functions optimally).

The contradiction between "quantity of substances or things" and "harmful factors produced by objects" is defined in accordance with principle No. 3, which defines the problem statement or suggests that the system design should be localized as much as possible (so that the objects perform their respective functions optimally), and in accordance with principle No. 39, which defines the problem statement or suggests that the system design should be localized as much as possible. Principle No. 39 defines the problem statement or suggests that a vacuum environment can be considered.

According to the design process of system contradiction, the TRIZ conflict matrix, inventive principle, and selection principle were used to obtain Table 1 to identify the contradiction process. Based on the inventive principle of selection in Table 1, the definition of the problem or suggestion is summarized by mapping the inventive principle interpretation to the definition of the problem or suggestion in Table 2.

Table 1. Identification of contradictory processes.

System Contradiction	TRIZ Contradiction	Inventive Principle	Selection Principle	Definition of the Problem or Recommendation
Use of multiple consumables can lead to bonding and clogging	The quantity of a substance or thing—stability	No. 15 No. 2 No. 17 No. 40	No. 15, dynamism No. 17, multidimensionality	Q1, Q2
	The quantity of a substance or thing—reliability	No. 18 No. 3 No. 28 No. 40	No. 3, local quality	Q3
Use of multiple consumables can lead to contamination	Quantity of the substance or thing—harmful factors produced by the object	No. 3 No. 35 No. 40 No. 39	No. 3, local quality No. 39, inert environment	Q3, Q4
Multiple nozzle replacement is time-consuming, and can lead toprint accuracy	The quantity of a substance or thing—productivity	No. 13 No. 29 No. 3 No. 27	No. 3, local quality No. 29, pneumatic and hydraulic mechanism	Q3, Q5
	Adaptability and versatility—ease of operation process	No. 15 No. 34 No. 1 No. 16	No. 1, split No. 15, dynamism	Q6, Q1
	Adaptability and versatility—productivity	No. 35 No. 28 No. 6 No. 37	No. 6, multifunctionality	Q7

Table 2. Definition of the problem or recommendation.

Number	Definition of the Problem or Recommendation
Q1	The system should be designed as dynamically as possible (to make it more flexible)
Q2	Should consider the object in space
Q3	System design should be as localized as possible (allowing objects to perform their respective functions at their best)
Q4	Vacuum environment can be considered
Q5	Pneumatic or hydraulic structure can be considered
Q6	The degree of segmentation of some parts should be increased
Q7	Where appropriate, make the object as versatile as possible
Q8	Make spitting more stable (required by the system itself)

3.3. Knowledge Push and Idea Generation

In the established knowledge graph, the search for the term "nozzle" and its first-level relations yields nodes that are close to the nozzle, as shown in Figure 6. The nozzle is connected to other design knowledge as both a head entity and a tail entity, such as <nozzle, having, rotor head> and <rotatable displaceable pipe, having, nozzles>. Some design knowledge can be directly used, and for useful design knowledge; further searches can be conducted at the next level, combining multiple factors to assist in producing design solutions. As shown in Figure 7, important nodes are expanded around the nozzle to find the necessary design knowledge; the nodes and paths can be flexibly changed according to the designer's understanding of the system and the mapping of problems and suggestions. Along the path of nozzles–rotatable displaceable pipe–plurality nozzles (tail)–ink jet–ink-repellant coating–plurality nozzles (head)–spray boom–shaft connecting means–one outlet nozzle clearing devices, the node "an outlet nozzle clearing device" and its path are obtained. Similarly, other design knowledge is obtained, and the searched design knowledge is used to generate creative, integrated, and generated design solutions.

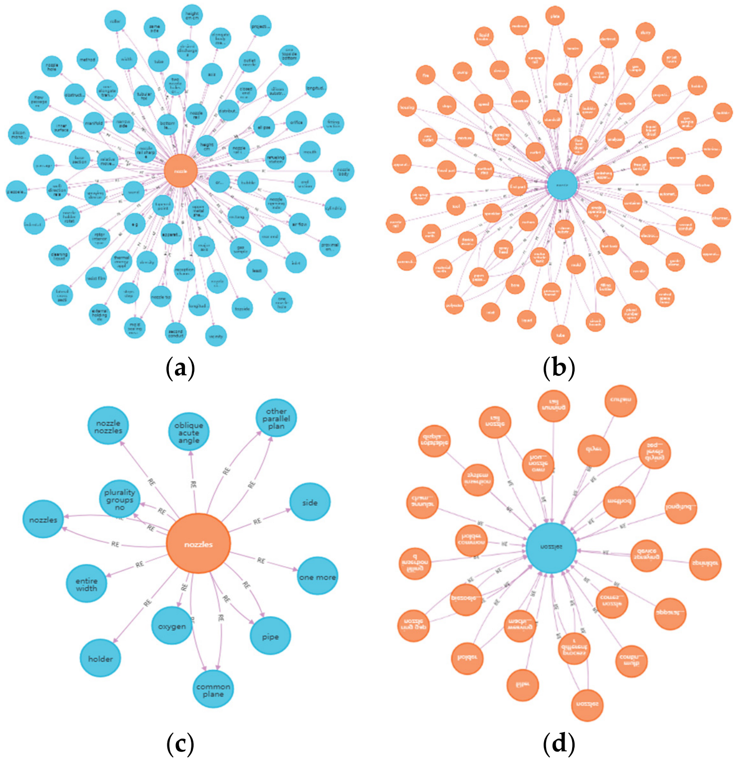


Figure 6. Display of design knowledge associated with the nozzle (first-level relationship): (**a**) "nozzle" is the design knowledge of the head entity, (**b**) "nozzle" is the design knowledge of the tail entity, (**c**) "nozzles" for the design knowledge of the head entity, and (**d**) "nozzles" for the design knowledge of the tail entity.

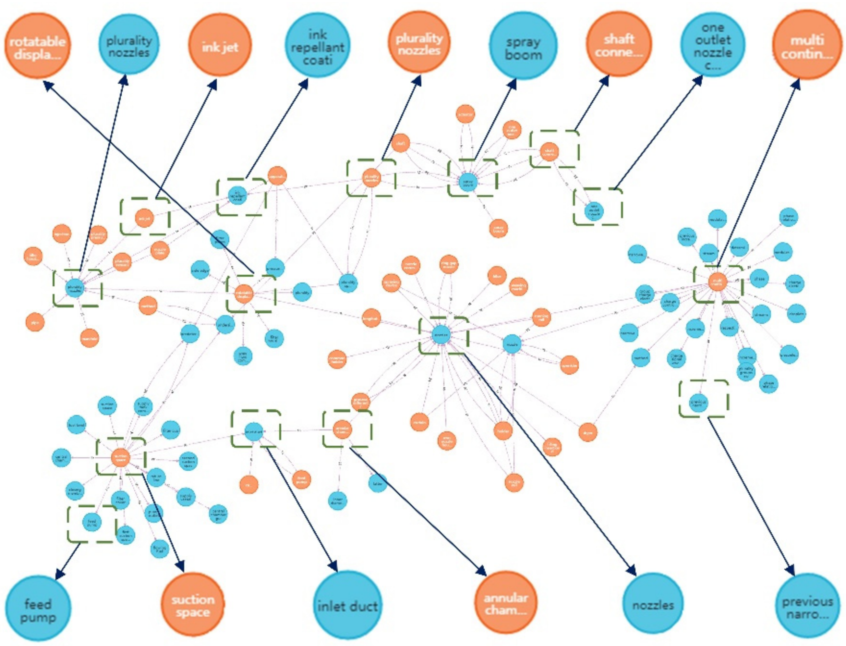


Figure 7. Knowledge search for nozzle design based on graph paths.

3.4. Creativity and Multi-Program Generation

Synthesize the design knowledge searched from the knowledge graph, combine the formulated problem and recommendations, view the recommended inventive principle from the perspective of SVOP semantics, and form a design solution. For example, the inventive principle has 15 dynamics: the measure directs the subject S to issue the action V, so that there is relative motion between the subsystems of the action object O, changing the structural parameters and motion parameters P of O. Here, the subject S is the product designer, and the action object O is the nozzle, using the design knowledge from the alternative database of design knowledge, which needs to make the system as flexible as possible. Also consider the conversion of space on the equipment; the touch head can be designed to replace the tube, and the nozzle remains unchanged so that the subsystem generates relative motion, the error caused by changing the nozzle is transferred to another space that does not affect the processing, etc. The above actions mainly adjust the relative position of the subsystem, changing the structural parameters of the nozzle. Part of the process of program generation is shown in Table 3.

Table 3. Solution-generation process based on knowledge graph and TRIZ.

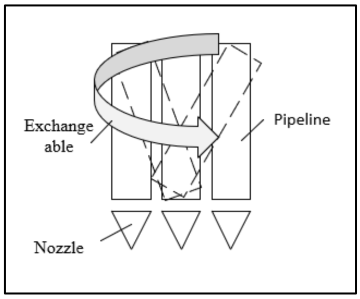
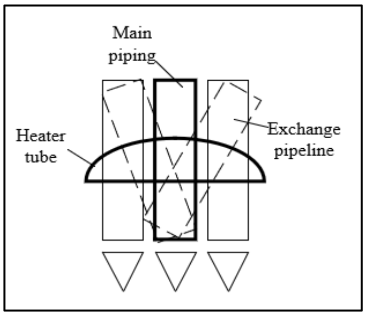
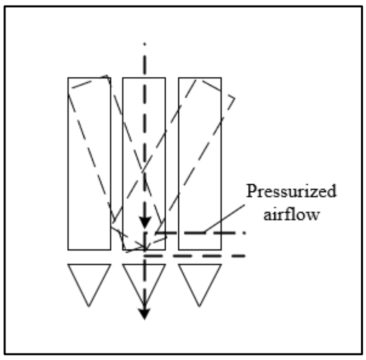
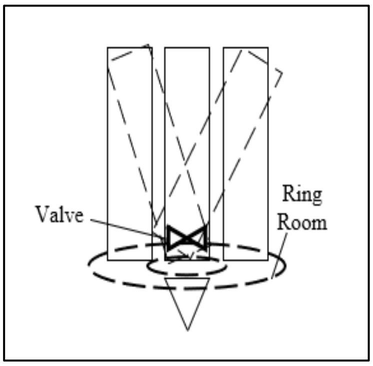
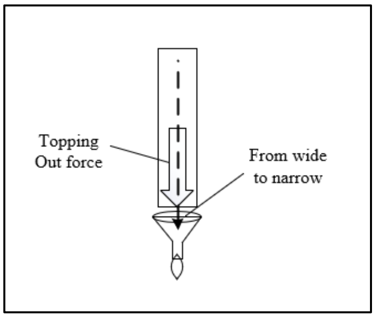
Design Knowledge from Graph	Problem Solved	Design Idea Generation
Rotatable displaceable pipe, divided plurality groups, nozzles, having apparatus exchange, and intersect oblique acute angle	P1, P2, P3 P6, P7	
Preheated conduit, comprising first conduit, and disposed first main body	P1, P2, P6	
Directing pressurized stream, gas, comprising pressure source, clearing outlet nozzle, comprising high pressure	P4, P5, P7	

Table 3. *Cont.*

Design Knowledge from Graph	Problem Solved	Design Idea Generation
Comprising valve element, account, spray valves, ring gap nozzle arranged, annular chamber enclosing, central chamber, and annular chamber	P1, P6	
Has ejection device and the narrowest spread	P8	
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3.5. Results

Finally, the combination of different knowledge and ideas from the appeal resulted in two nozzle design solutions.

Scheme 1 comprises components such as the nozzle body, feed tube, heater, gas chamber, discharge tube, and others, collectively forming a comprehensive and functional structure, which is illustrated in Figure 8. Addressing the issue of inadequate spitting in the 3D-printing nozzle, this device employs an air pump to exert pressure on the discharge tube through an air hole. This action augments consumable extrusion, ensuring that molten consumables flow smoothly from the nozzle at an optimal rate. To tackle the problem of nozzle blockage during 3D printing, this apparatus integrates multiple removable heaters. These heaters allow for flexible temperature adjustments in proximity to the throat channel, preventing the premature melting of printing consumables due to excessive heat. Moreover, the amplified air pressure resulting from the air pump aids in thorough consumable ejection, minimizing accumulation and blockage within the discharge tube. In response to the need for diverse consumable outputs without replacing the 3D-printing nozzle in situ, the device incorporates a separate melting chamber within the nozzle body. A pull-out isolation plate regulates the flow of distinct printing consumables. The chamber is infused with gas via an air pump, effectively reducing consumable residue when traversing the nozzle's front section. This strategic approach prevents the mingling of different consumables within the nozzle, thus safeguarding print quality.

Scheme 2 employs a rotational configuration to replace the parallel pipe and achieve automated barrel switching. This system encompasses several key components, namely the feeding assembly, barrel assembly, rotating assembly, housing, and heater, as illustrated in Figure 9. The feeding assembly comprises a rotating platform housing multiple wire feeders that are evenly distributed on its surface, and each is equipped with a corresponding feed port. Within the barrel assembly, an equal number of barrels are incorporated to facilitate the wire supply mechanism. The rotating assembly integrates a two-shaft motor and a planetary gear mechanism, interconnected at the motor's lower output. The system's housing is cylindrical in structure, featuring a discharge port and a nozzle at the base, while the heating element is positioned beneath the housing's bottom, near the nozzle side. The system employs external heating to melt the printing wire, preventing material blockages within the nozzles. A planetary gear mechanism regulates each barrel, ensuring precise alignment with the outlet to facilitate the transition between various printing materials. The resulting solution intricately subdivides the nozzle system, augmenting system flexibility and enabling each component to optimize its functionality. Consequently, this approach partially addresses the identified problem, enhancing the system's overall performance.

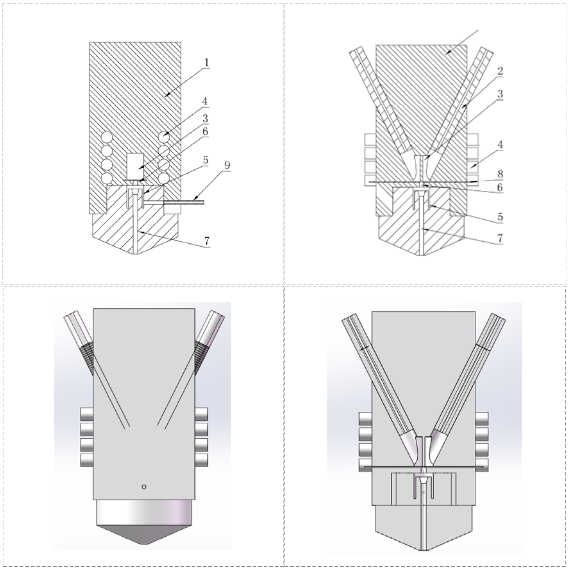

Figure 8. Multi-material 3D-printing nozzle SARS-CoV-2 detection in clinical throat-swab samples. (1) Nozzle body, (2) inlet tube, (3) melting chamber, (4) heater, (5) gas chamber, (6) first discharge tube, (7) second discharge tube, (8) isolation plate, and (9) gas guide tube.

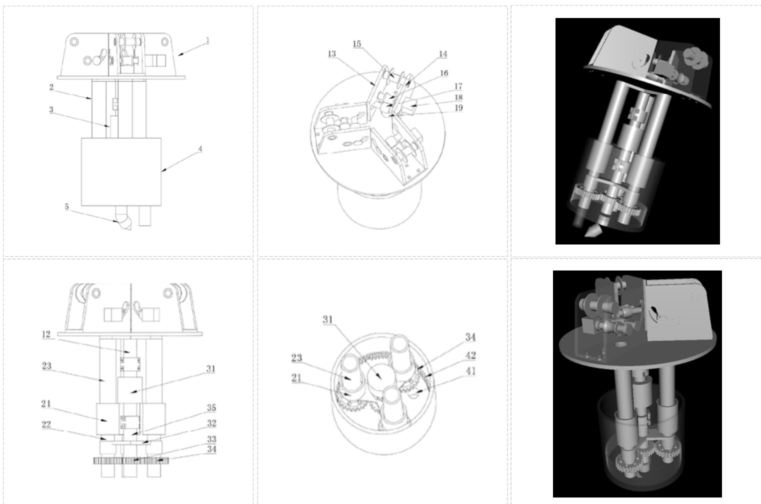

Figure 9. Multi-material 3D-printing nozzle. (1) Feeding assembly, (2) barrel assembly, (3) rotary assembly, (4) housing, (5) heater, (12) connecting shaft I, (13) supporting plate I, (14) supporting plate II, (15) winding material roller, (16) rotating roller, (17) clamping roller, (18) driving motor, (19) inlet, (21) upper barrel, (22) lower barrel, (23) material tube, (31) double shaft motor, (32) planetary frame, (33) center gear, (34) planetary gear, (35) connecting shaft II, (41) discharge port, and (42) ring.

4. Conclusions

The introduction of a TRIZ-KG-based design methodology is a novel attempt. The combination of innovation method theory and knowledge mapping can help designers better understand requirements. It can help designers to think outside of the box when they encounter blockages in the design process and create new solutions by guiding the design process through a systematic analysis and evaluation. The main work of this paper was to propose a TRIZ-KG-based design methodology that effectively establishes a systematic framework for problem solving and innovation so that it can be effectively applied in the design process, transforming design flaws into opportunities for innovative solutions.

In this paper, the feasibility of the method was verified through the design of a multi-material 3D-printing nozzle as a case study. First, the designer analyzed the current defects of the printhead according to the requirements, uncovered the design problem, and then transformed the design problem into the system contradiction corresponding to the design; second, the system contradiction was transformed into the design direction through the TRIZ Conflict Matrix and Invention Principle, that is, the definition of the problem or the proposal proposed in Table 1; third, the design direction was subjected to a knowledge search in the knowledge graph to help the designer's design of the design problem's dispersion solving in order to obtain design ideas; fourth, the obtained design ideas were verified by drawing through 3D drawings, and two design solutions that satisfied the requirements are formed.

Based on the results of the proposed case, it was shown that innovative solutions can be found in regard to multi-material 3D-printing nozzle design by using the combined TRIZ-KG approach. This approach provides designers with a systematic thinking framework that helps them overcome technical difficulties and propose solutions that better meet their needs. In the future, we will further optimize this design method and promote the development of multi-material 3D- and 4D-printing technology with a multiphysics analysis in practical applications [12,13].

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