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ENHANCED SPATIAL VISUALIZATION OF INTERNAL FEATURES THROUGH A SECTIONED, 3D-PRINTED INSTRUCTIONAL MODEL

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Abstract: *Orthographic projection remains a foundational, yet challenging, concept for students in technical drawing and engineering graphics, often hindered by the difficulty of translating a 3D object's internal features into distinct 2D views. This paper presents the design, fabrication, and pedagogical application of a novel, sectioned, 3D-printed instructional model created to bridge this spatial visualization gap, with a specific focus on clarifying sectional views. The model is a complex geometric part that is physically sliced along a predetermined cutting plane. A key innovative feature is the highlighting of the resulting cut surface, providing a simultaneous, tangible, and unambiguous link between the abstract cutting plane and the exposed material. Using additive manufacturing (3D printing) allowed for rapid iteration and clear visual distinction between components. Initial observations suggest this hands-on tool significantly improves students' comprehension of sectioned views, the concept of the cutting plane, and the representation of hidden lines. The model serves as an effective pedagogical aid, offering a superior alternative to purely virtual or static drawing-based instruction, and is a valuable contribution to engineering graphics education methodology.*

Key words: Orthogonal Projection, 3D Printing, Spatial Reasoning, Engineering Graphics, Sectional View

1. INTRODUCTION

The capacity for spatial visualization is paramount in engineering, architecture, and design disciplines. It represents the cognitive ability to mentally manipulate two- and three-dimensional objects, a skill fundamentally tested and honed through the mastery of orthogonal projection. This drawing technique is the globally accepted standard for communicating precise dimensional and geometric information necessary for manufacturing and assembly. However, educators consistently identify the interpretation of sectional views, a technique essential for revealing internal geometry, as a critical barrier to entry for novice students [1], [4]. The reliance on interpreting complex hidden lines and mentally constructing a three-dimensional solid from two-dimensional projections places a heavy cognitive burden on beginners.

Traditional methods of instruction, relying predominantly on static 2D illustrations, virtual CAD models displayed on a screen, or rudimentary whiteboard sketches, often fail to provide the essential haptic and physical connection necessary for all learning styles [3], [8]. While modern CAD environments allow for dynamic manipulation, the screen interface still creates a psychological barrier, lacking the tactile reality needed to firmly grasp the concept of sectioning, that is, the imaginary removal of material to reveal interior structure [5]. This cognitive challenge is particularly acute when interpreting the invisible, or hidden, internal features and complex sectional planes [4].

This paper addresses this pedagogical shortfall by introducing a novel educational artifact: a precisely designed, sectioned part created via **Additive Manufacturing (3D Printing)** [2]. The model is constructed to be split along a defined cutting plane, allowing students to physically separate the part and observe the resulting internal cross-section. This physical demonstration directly addresses the core difficulty of sectional views: distinguishing the material that is cut from the geometry that lies beyond the cutting plane. The model's use of high-contrast colors further emphasizes the boundary of the cross-section, eliminating ambiguity. The primary objective of this work is to detail the methodology used to create this physical aid and to establish its theoretical basis for enhancing student understanding of sectioning principles and internal feature visualization. We hypothesize that by providing a direct, physical representation of the sectioning process, this model will substantially accelerate the

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development of spatial reasoning skills among students of technical drawing and modeling.

The remainder of the paper is structured as follows: Section 2 reviews the pedagogical literature supporting tangible learning aids and cognitive load theory; Section 3 details the CAD design, manufacturing, and color delineation methodology; Section 4 discusses the pedagogical application and predicted educational outcomes; and Section 5 presents the conclusions and outlines avenues for future quantitative research.

2. THEORETICAL FRAMEWORK: THE ROLE OF TANGIBLE ARTIFACTS IN SPATIAL COGNITION

The capacity for spatial visualization is recognized as a critical predictor of success in engineering disciplines [1], [7]. The integration of physical models into technical education is supported by established cognitive theories. Developmental psychology, particularly the work of Piaget, emphasizes that learning progresses from concrete operational thought (requiring manipulation of physical objects) to formal operational thought (abstract reasoning). For subjects like engineering graphics, which demand the synthesis of abstract geometric rules with real-world forms, concrete examples are invaluable [8]. Physical models provide essential grounding for students who struggle with initial visualization skills.

2.1. Haptic and Visuospatial Learning

Learning aids that incorporate a haptic component (touch and manipulation) engage a wider range of sensory inputs than purely visual or auditory instruction [3]. Haptic feedback provides a direct, intuitive understanding of geometry, form, and internal complexity that is difficult to convey through a monitor. The physical act of holding, rotating, and separating the model engages kinesthetic memory, forming a more robust mental model of the object [8]. Furthermore, studies on visuospatial learning confirm that individuals with lower initial spatial ability show the most significant improvement when provided with physical models to inspect, rotate, and disassemble. The tactile component of the split sectional model provides immediate confirmation of the hidden internal features.

The proposed instructional model capitalizes on this by offering a tangible representation of internal features. Instead of requiring students to mentally translate a 2D line (a hidden line) into a 3D feature (a bore or slot), they can physically separate the model, eliminating the abstraction and allowing them to instantly verify the true geometry and cross-section created by the cutting plane.

2.2. Additive Manufacturing as a Pedagogical Tool

The advancement of affordable Additive Manufacturing (AM), or 3D printing, has democratized the creation of specialized educational aids [2]. Unlike traditional manufacturing methods, AM allows for the rapid creation of complex internal features, high-fidelity geometry, and, crucially for this project, the use of contrasting colors to highlight features such as cutting planes and sectioned surfaces. The ability to create complex internal cavities, which would be extremely expensive or impossible via traditional subtractive manufacturing, makes AM the ideal method for producing such pedagogical tools [10]. The cost-effectiveness and accessibility of Fused Deposition Modeling (FDM) technology ensure that institutions can produce multiple models for lab use, thereby maximizing student contact time with the physical artifact.

2.3. Cognitive Load Theory (CLT) in Visualization Instruction

Cognitive Load Theory (CLT) posits that learning effectiveness is limited by the capacity of working memory. CLT identifies three types of cognitive load: intrinsic, extraneous, and germane. In the context of engineering graphics, the mental effort required to mentally project a 3D object from its 2D views contributes significantly to extraneous cognitive load, as students must expend resources on translation rather than conceptual understanding [11].

The sectioned, 3D-printed model serves as an effective instructional design solution to reduce this extraneous load. By externalizing the mental sectioning process, that is, by physically performing the cut and visually contrasting the material cut versus the remaining material, the instructional model minimizes the non-essential mental processing. This allows cognitive resources to be redirected toward

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"germane cognitive load", which is the processing and construction of schemas (deep understanding) necessary for spatial reasoning. By simplifying the visualization task, the physical model facilitates the effective encoding of the geometric rules of sectioning into long-term memory [11]. This direct sensory input helps transform a highly abstract, high-extraneous-load task into a more concrete, high-germane-load learning experience.

3. DESIGN AND METHODOLOGY OF THE 3D-PRINTED SECTIONAL MODEL

The instructional model was engineered as a single, multi-component assembly representing a critical case study in sectioning complexity. The chosen geometry (a part we term the "Sectional Test Block") was specifically engineered to include features that commonly confuse students: internal bores, ribs/webs (which follow special sectioning conventions), and features requiring hidden lines when viewed externally. The deliberate complexity ensures the model is relevant for intermediate and advanced technical drawing concepts.

3.1. Geometric Design and CAD Workflow

The model is based on a rotational block that includes the following features:

3.1.1. A central step-bore.

3.1.2. A blind slot on the horizontal surface, used to illustrate depth.

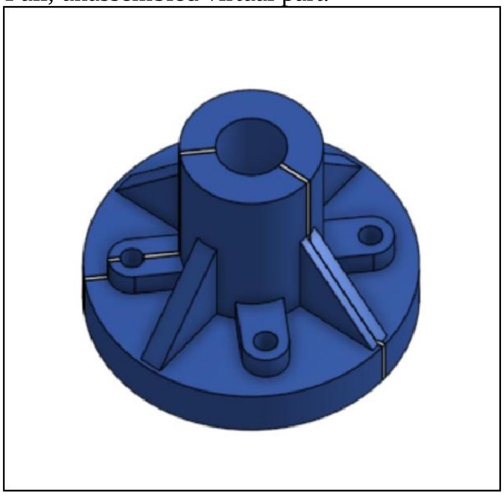
3.1.3. A defined cutting plane passing through the block, resulting in a complex sectional profile.

3.1.4. Features requiring hidden lines when viewed externally.

Figure 1: Comparison of the CAD model and the physical 3D-printed Sectional Test Block.

(a) CAD Model

Full, unassembled virtual part.



Sectioned virtual part, showing geometry.

(b) Physical 3D Print

Full, assembled physical part.

Sectioned physical part, showing geometry.

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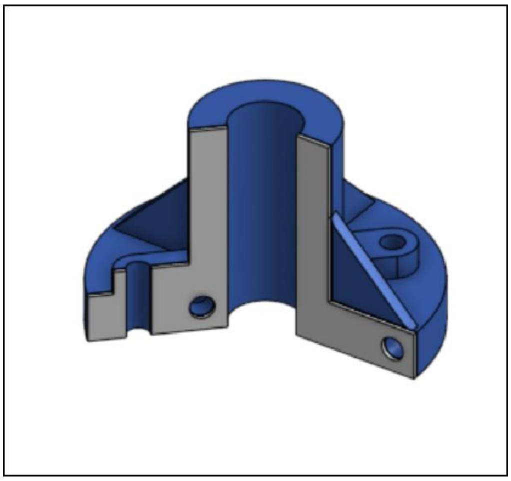

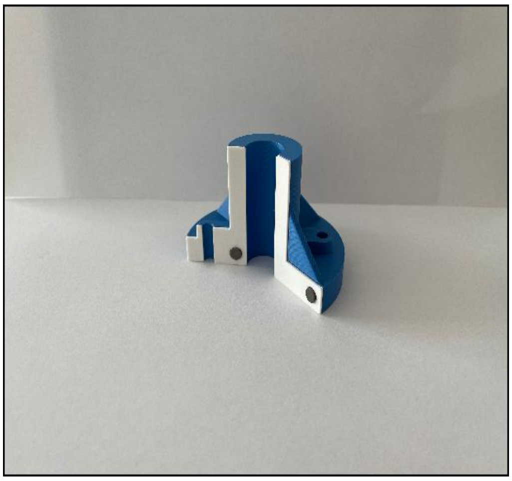

The design process began in a commercial CAD environment (e.g., SolidWorks or Fusion 360). Critical attention was paid to the cut geometry, ensuring the cutting plane perfectly intersects the intended features. The part was designed as a single solid and subsequently split along the desired plane using the 'Split Body' feature. A minimal clearance (approximately 0.1 mm) was added to the mating faces to ensure the parts could be cleanly separated and reassembled after FDM printing, compensating for material shrinkage and tolerances inherent in the process.

3.2. Model Segmentation and Colour Delineation

The complete system consists of the main part, which is segmented into two removable portions along the cutting plane. The design emphasizes two key aspects:

3.2.1. The Sectioned Part (Model): The main block, sliced along the predetermined cutting plane. The critical feature is the sectioned face, which is printed in a high-contrast color (e.g., white in the image) to clearly differentiate the material cut by the plane. This component is designed to be fully separable, allowing students to hold and manipulate the exposed internal surfaces.

3.2.2. Highlighting Internal Features: By removing the sectioned portion, the student is directly exposed to the internal geometry that would normally be represented by "hidden lines" in an orthogonal view. The physical separation transforms an abstract concept (the cutting plane) into a tangible surface. The high-contrast color is paramount, as it visually mimics the hatch lines of a 2D section, providing an unambiguous physical equivalent.

3.3. Additive Manufacturing Parameters

The components were fabricated using Fused Deposition Modeling (FDM) technology, primarily due to its affordability, accessibility, and ability to handle multi-color prints through simple filament swaps. This choice ensures the replicability of the teaching aid across educational budgets. The key parameters used to ensure fidelity and functionality were:

- **Material:** PLA (Polylactic Acid) was chosen for its low cost, ease of printing, structural rigidity, and ability to accept different color filaments for contrast. PLA is also safe for frequent student handling.
- **Layer Height:** 0.2 mm was selected as a balance between print speed and the need to achieve necessary detail and smoothness, especially for the intricate features and the large, sectioned surface.
- **Infill Density:** A sparse infill (e.g., 20% cubic) was used to minimize material cost and print time, without compromising the rigidity required for handling.
- **Color Coding:** Two distinct colors were employed: a neutral primary color (blue in the image) for the main body and a high-contrast color (white in the image) for the sectioned face of the Test

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Block, which represents the material "cut" by the imaginary plane. This dual-color strategy is achieved by pausing the FDM printer at the exact layer where the cutting plane surface begins.

4. PEDAGOGICAL APPLICATION AND DISCUSSION

The primary benefit of this model lies in its ability to facilitate the immediate visualization of internal features and the sectional principle, converting an abstract geometric problem into a tactile exercise. The pedagogical discussion centers on two key areas: the clarification of internal geometry and the cognitive benefits of tactile learning, as well as the practical integration of the tool.

4.1. Clarifying the Cutting Plane and Sectioning Conventions

Interpreting a sectional view is arguably the most challenging aspect of technical drawing [4]. Students often struggle to differentiate between the imaginary cutting plane used to reveal internal features and the resulting section view [4]. The model provides clarity in several critical areas of sectional drawing practice:

- Material vs. Void: The physical sectioned face, highlighted in high-contrast color, acts as a definitive visual anchor for the concept of the cutting plane. It provides the exact boundary that the corresponding 2D hatch lines would depict, unequivocally showing what material is cut.
- Hidden Lines: By physically removing the sectioned portion, the internal geometry (bores, slots, etc.) is fully exposed in three dimensions. This directly addresses the confusion surrounding hidden lines, as the student sees the true spatial configuration that these lines represent, thereby validating the need to convert hidden lines to solid lines in the section view.
- Conventional Practices: Since the test block includes features such as structural ribs or webs (visible in Figure 1), the model can be used to visually explain sectioning exceptions, the convention that thin elements are often not sectioned, even if the cutting plane passes through them, to avoid misleading interpretation.

4.2. Cognitive Benefits of the Tactile Model

The model provides significant cognitive benefits by directly engaging multiple learning senses [3]. Tactile learning is particularly effective for students who struggle with abstract geometric manipulation [8], [11].

- **Reduced Cognitive Load:** By externalizing the mental rotation and feature translation steps, the model, in line with CLT principles, allows students to focus cognitive resources on understanding the geometric principles of sectioning, rather than struggling with visualization.
- **Universal Accessibility and Remediation:** The tactile nature of the model benefits diverse learners, providing a critical physical complement to purely visual instruction. It is highly effective for use in spatial visualization remediation programs, which are frequently used to boost the performance of engineering students with low initial spatial test scores [1], [7]. The physical artifact caters to kinesthetic and low-spatial-ability learners [8], [11].
- **Self-Correction and Verification:** The model provides a constant, unambiguous physical reference, promoting self-correction and iterative learning as students compare their drawn projections with the model's actual geometry.

4.3. Integration into Curriculum and Pedagogy

The model is designed to be integrated into the technical drawing curriculum across three distinct pedagogical phases:

- **Phase 1: Lecture Demonstration (Conceptual Introduction):** The model is introduced during the lecture where sectioning is first presented. The instructor physically performs the cutting action (separating the halves) to illustrate the concept of the cutting plane, using the high-contrast surface to define the cross-section. This shifts the focus from an abstract line on a drawing to a tangible material removal.

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- **Phase 2: Lab Practice (Active Learning):** Students are given access to the models in the lab. They are tasked with sketching or modeling the sectional view for the part, while using the physical model for verification. They manipulate the model to verify their understanding of which lines become visible, and which are eliminated by the cut. This serves as an immediate, physical feedback loop.
- **Phase 3: Remedial and Self-Study (Reinforcement):** The models are made available outside of class time. For students struggling with sectional interpretation, manipulating the model provides a powerful, private, and non-judgmental remediation tool. Its tactile nature supports self-guided reinforcement of the challenging geometric concepts [7].

5. CONCLUSIONS AND FUTURE WORK

This paper has presented a comprehensive methodology for designing and fabricating a novel, sectioned, 3D-printed instructional aid for teaching orthogonal projection and sectional views. The model uniquely integrates a physically sectioned part, with a high contrast cut face, creating a powerful, self-verifying

tactile learning experience that directly maps the abstract principles of the cutting plane onto a concrete 3D object. By externalizing the complex mental visualization required for sectional views, the model effectively reduces extraneous cognitive load and maximizes learning efficacy, particularly for novice students.

The contribution of this work lies in offering a verifiable, manufacturable, and pedagogically sound solution to one of the most persistent difficulties in engineering graphics education: the successful visualization of internal geometry [1], [7]. The affordability and customization enabled by modern FDM 3D printing make this methodology highly reproducible and adaptable across different academic institutions and curriculum requirements [2], [10].

5.1. Future Research Directions

Future work will focus on the quantitative validation of this teaching methodology [7]. A controlled experiment comparing two cohorts, one using the 3D-printed model and one using traditional static drawing instruction (including virtual CAD models), will be implemented. The primary metric will be performance change on standardized spatial reasoning tests (e.g., Purdue Spatial Visualization Test) and drawing accuracy scores related to sectional views over a single academic term [6].

Furthermore, the physical design will be iterated to enhance its instructional versatility. This includes developing modular components, allowing professors to quickly change the complexity of the internal features (e.g., swapping a simple bore for a keyway) without redesigning the entire model [10]. We also plan to explore variations using dual-extrusion 3D printing to create the cutting plane surface in a highly transparent material, allowing students to visualize the cutting plane “before” physical separation, further enhancing the cognitive link between the abstract tool and the physical result. Finally, a longitudinal study investigating the retention rate of spatial skills enhanced by this tactile model, compared to purely digital methods, would provide valuable data on the model's long-term pedagogical effectiveness.

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