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スケッチベース可動オブジェクトの設計支援インターフェースの研究

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This thesis proposes a sketch-based design support interface that automatically generates articulated, 3D-printable objects from a single side-view sketch. Recent progress in generative AI and digital fabrication has lowered the barrier to creating visually plausible 3D models; however, designing objects that physically move remains difficult for users because it requires mechanical knowledge such as tolerance design, collision avoidance, and joint fabrication. While state-of-the-art image-to-3D techniques can reconstruct static geometry from text or images, they typically output a single solid mesh without functional structure, resulting in models that look complete on screen but cannot be manipulated as toys or mechanisms in the physical world. The goal of this research is to bridge this gap by connecting intuitive sketch input with computational fabrication methods so that users can transform their drawings into tangible artifacts that can be touched and moved.

The proposed system takes a hand-drawn line sketch as input and produces an STL model that can be fabricated on a consumer-grade fused deposition modeling (FDM) 3D printer. The core idea is to combine a multi-stage generative pipeline for robust shape creation with an automated joint-generation pipeline that embeds mechanical articulation into the generated mesh. Starting from a sparse sketch, the system first generates a realistic toy-like image while preserving the original pose and silhouette. This step is introduced because direct sketch-to-3D generation is unstable: hand-drawn sketches often lack shading and depth cues and contain noise such as line jitter and incomplete contours, which can lead to thin, broken, or geometrically inconsistent 3D reconstructions. By converting the sketch into a dense, shaded, and domain-constrained toy image (e.g., smooth plastic-like surfaces on a clean background), the system stabilizes downstream 3D reconstruction and encourages the generation of watertight, smooth meshes that are more suitable for boolean operations and fabrication.

Next, the system reconstructs a 3D mesh from the generated image using a feed-forward single-image 3D generation approach. This stage addresses the inherent ambiguity of recovering occluded surfaces from a single viewpoint (e.g., the Janus problem, where duplicated facial structures may appear). The reconstructed mesh is exported in GLB format and serves as the basis for structural analysis. To enable articulation, the system estimates a kinematic skeleton and skinning information from the mesh using an automatic rigging technique that does not require a predefined template category. The estimated joint locations are interpreted not merely as animation pivots, but as physically meaningful segmentation and joint-placement cues for fabrication. This re-interpretation is essential: computer graphics rigging typically produces smooth deformations without physical separation, whereas a physical toy requires explicit part separation, rotational axes, sockets, and clearances.

Using joint position information estimated by the skeleton estimation model, we develop an algorithm that applies physically functional joint structures to a 3D model. Joint locations and types are manually specified by the user. The system supports two representative joint types: ball joints for multi-directional articulation and hinge joints for single-axis rotation. For each joint, feasible geometric parameters are determined by analyzing the local mesh thickness around the joint, estimating the maximum allowable joint size, and optimizing the joint radius under geometric constraints. These parameters are then used to generate parametric cutter shapes for sockets, axial holes, and motion clearances. By converting bone information originally estimated for CG applications into geometric fabrication data that accounts for 3D-printing clearance and structural strength, the proposed method enables real-world articulation. The final articulated model is generated through constructive solid geometry (CSG), producing a single-piece printable model with the internal

cavities and openings required for movement.

To reduce the risk of failure in fully automated generation, the system provides an interactive web-based user interface that visualizes intermediate results and allows users to adjust joint positions and parameters when needed. The interface guides the user through a step-by-step workflow: sketch input, image generation, 3D reconstruction, rigging, joint selection, cutter preview, and final STL export. During joint design, the system displays joint candidates, differentiates joint types visually, and supports iterative refinement by enabling changes to cutter orientation, joint center offsets, clearance values, and neck lengths. This human-in-the-loop mechanism aims to maintain ease of use while offering enough control to recover from common failure modes such as joints placed too close to the surface, insufficient clearance, or undesirable motion ranges.

The implementation integrates multiple AI models and geometry-processing components under practical computational constraints. Because each model may require different dependencies and CUDA versions, the system orchestrates inference by launching separate Conda environments and passing intermediate files between stages. The geometry module is implemented in Python using trimesh for mesh processing and repair, SciPy for parameter optimization, and a robust boolean engine to mitigate non-manifold errors that are common in AI-generated meshes. This architecture supports end-to-end processing within an interactive timescale suitable for exploratory design.

The contributions of this thesis are threefold. First, it presents an end-to-end pipeline that converts a single side-view sketch into an articulated 3D model that can be fabricated on consumer 3D printers, thereby extending sketch-based modeling from static shape creation to functional object design. Second, it proposes a method for translating learned rigging outputs into fabrication-oriented joint placement and parameterization, including automatic sizing and clearance generation based on local geometric analysis. Third, it introduces an interactive interface that exposes key intermediate representations and allows lightweight user intervention, balancing automation with reliability.

Through technical evaluation and a user study, we assess whether the proposed pipeline can reliably generate movable, 3D-printable models from simple side-view sketches, and whether the interactive interface helps users refine joint placement and fabrication parameters when automatic results are imperfect. The results indicate that the proposed approach can generate a variety of animal-like articulated toys while lowering the expertise required for mechanism design. Remaining challenges include improving robustness for extreme poses, thin structures, and highly stylized sketches; extending joint types and motion constraints; and incorporating printing-material considerations and post-processing guidance. Overall, this research demonstrates that combining generative AI with computational fabrication and interactive control can democratize the creation of physically functional artifacts from intuitive 2D sketches.