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MASTER THESIS

A Method for Image Generation Using Conditional Multi-Views

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Machine Learning, Generative Models, Diffusion

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Streszczenie

Dodaj streszczenie pracy w języku polskim. Staraj się uwzględnić wymienione na stronie tytułowej słowa kluczowe. Uwaga przedstawiony rekomendowany szablon dotyczy pracy dyplomowej pisanej w języku angielskim. W przeciwnym wypadku, student powinien samodzielnie zmienić nazwy „Chapter” na „Rodział” itp stosując odpowiednie pakiety systemu L^AT_EXoraz ustawienia w pliku *latex-settings.tex*.

Abstract

Streszczenie w języku angielskim.

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1. Introduction TODO

W pracy formułuje się cele o charakterze badawczym wymagające doboru i zastosowania metod badawczych, wykorzystując wiedzę teoretyczną oraz naukową. Wskazane jest przedstawienie, co nowego jest zaproponowane w pracy oraz podanie ograniczeń i słabych/mocnych stron opracowanego rozwiązania (jeżeli dotyczy). Rozdział wprowadzający powinien służyć czytelnikowi do zrozumienia celu pracy.

1.1. Problem Statement

W tej sekcji student powinien przedstawić bliżej problem, którym chce się zmierzyć. Jasno zdefiniuj problem badawczy. Podaj swoje cele, zadania i pytania badawcze. Wyjaśnij znaczenie badania. Określ ograniczenia badań.

1.2. Thesis Objectives

W tej sekcji powinny zostać przedstawione konkretne działania, które określają pracę studenta w celu rozwiązania problemu.

2. Related Work

In this chapter, I provide a comprehensive review of existing approaches relevant to multi-view image generation.

The chapter begins by introducing the fundamental task of Novel View Synthesis (NVS) and its significance. We then delve into traditional 3D reconstruction techniques (Section 2.1) and their inherent limitations, particularly for sparse-input scenarios, which motivates the exploration of generative methods. Subsequently, the discussion shifts to the foundational principles of Deep Generative Models for Image Synthesis, with a focus on diffusion models (Section 2.2).

Building on this, we explore various methods for Conditioning Diffusion Models for Enhanced Control and New Tasks (Section 2.3), including the crucial role of camera parameter encoding and the concept of lightweight adaptation through adapters.

The core of the chapter then examines state-of-the-art Diffusion-based Multi-View Image Generation techniques (Section 2.4), covering both single reference image novel view synthesis and architectures for coherent multi-view generation, including specialized multi-view adapters.

2.1. Traditional 3D Reconstruction Approaches

Simultaneous Localization and Mapping (SLAM) is a fundamental concept in the field of computer vision and robotics. It refers to the process of simultaneously estimating the camera's position and orientation in a 3D environment while mapping the environment itself. Originally, SLAM was used to track the position of a robot in a 3D space, but it has since been applied to a wide range of problems, including augmented reality, medical applications and novel view synthesis.

SLAM works by processing sensor data in real-time to create a map of the unknown environment while simultaneously tracking the position of the sensor within that map. This process typically involves several key steps:

1. **Feature Detection:** Identifying distinctive points or features in the environment from sensor data
2. **Data Association:** Matching observed features with previously mapped features
3. **State Estimation:** Updating the estimated pose of the camera and the map of the environment
4. **Loop Closure:** Recognizing when the sensor has returned to a previously visited location and adjusting the map accordingly to reduce accumulated errors

To address these requirements, researchers have concentrated on creating techniques for machines to independently build ever more precise scene representations. This integration of

robotics, computer vision, sensor technology, and recent advancements in artificial intelligence has shaped this field.

Typically, SLAM techniques use a combination of data sources, such as images, laser range scans, sonars and GPS to effectively map an environment. In this work I will focus on the use of images for 3D reconstruction.

2.1.1. Structure from Motion Pipeline

One of the most popular methods for 3D reconstruction from images is COLMAP [25]. COLMAP is a general-purpose structure-from-motion (SfM) [12] system that can automatically reconstruct 3D scenes from a collection of images. It is a popular choice for 3D reconstruction due to its accuracy, speed, and ease of use.

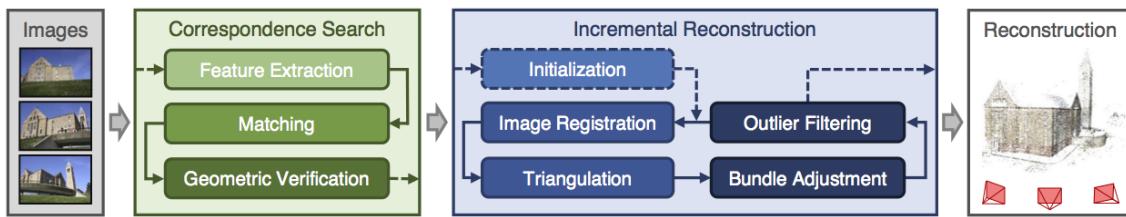


Figure 2.1: COLMAP pipeline

Structure from Motion works in two main steps [Figure 2.1]:

1. **Correspondence Search:** Identify the unique landmarks (features) in all of the images and match the same landmarks across images.
2. **Incremental Reconstruction:** Estimates the camera poses and triangulates 3D points through an iterative process.

First step of correspondence search is feature extraction. COLMAP uses SIFT [16] and ORB [24] methods to extract features from images. Scale-invariant feature transform (SIFT) is a method for detecting keypoints that contrast with their surroundings and describing the local image content around them. It is invariant to rotation and scale, making it robust for matching features across images taken from different viewpoints and distances. Oriented FAST and Rotated BRIEF (ORB) is a more computationally efficient alternative to SIFT, combining a high-speed FAST detector with optimized descriptors for rotation invariance, offering comparable matching performance with significantly reduced computational requirements.

Second step is matching features across images. Feature matching is a process of finding the best matches of features across the images. COLMAP uses a variant of the FLANN [19] library to find the best matches for each feature. FLANN is a library for performing fast approximate nearest neighbor searches in high dimensional spaces. Feature matching is visualized in Figure 2.2.

Then the geometric verification step uses the prior knowledge about the camera model and motion to remove outliers, preparing the verified feature matches for the subsequent Incremental Reconstruction phase.

When it comes to Incremental Reconstruction, the process is as follows:

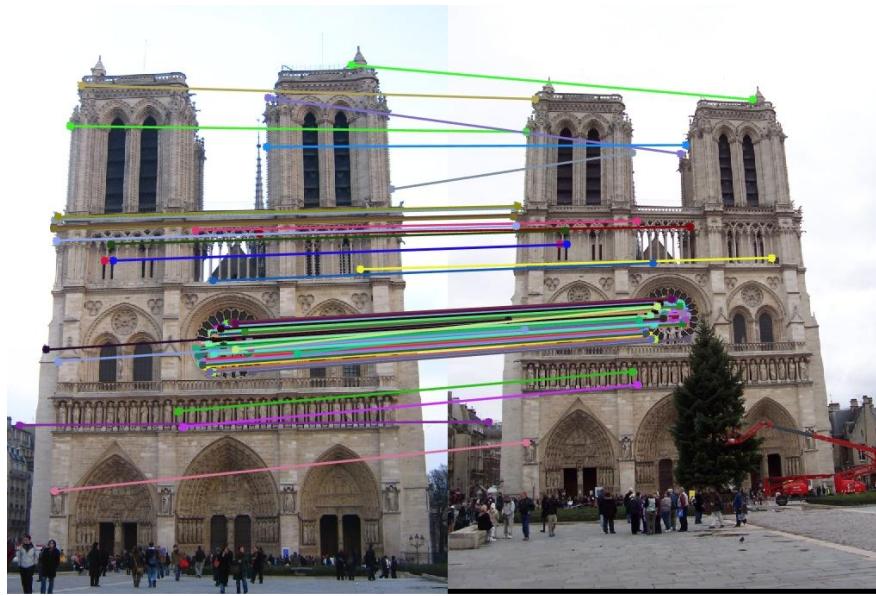


Figure 2.2: Feature matching result

1. **Camera Pose Estimation:** Estimate the camera location and direction in 3D space for each image.
2. **Triangulation:** Triangulate 3D points of the observed objects from the camera poses and matched features.
3. **Bundle Adjustment:** Refine the camera poses and 3D points to minimize the reprojection error.

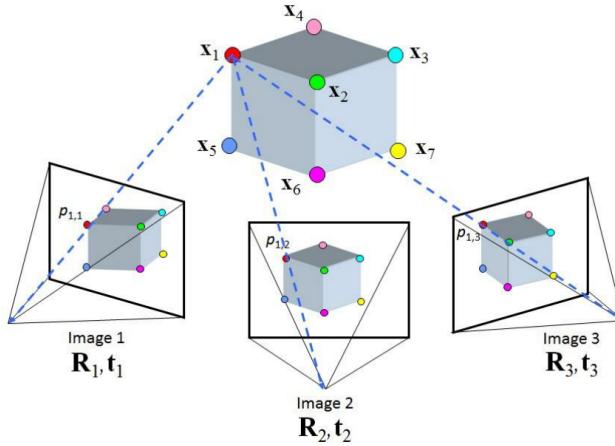


Figure 2.3: Camera pose estimation

The camera pose estimation (visualized in Figure 2.3) starts with an initialization step, where the initial pair of images and matched features between them are used to estimate the camera pose. Then, the algorithm proceeds to the loop (Figure 2.1), where the next image

is registered to the reconstruction and the camera pose is estimated again (triangulation step). After that the bundle adjustment step is performed to refine the camera poses and 3D points to be consistent with the entire dataset with images of a given scene. This optimization process typically uses the Levenberg-Marquardt algorithm to minimize reprojection error. This process is repeated for each subsequent batch of images, updating the camera poses and 3D points.

2.1.2. Methods for 3D Reconstruction

The field of 3D reconstruction encompasses various approaches beyond the basic Structure from Motion pipeline. These methods can be broadly categorized into two groups: sparse reconstruction (like SfM) and dense reconstruction methods.

Dense Reconstruction Methods

While SfM provides camera poses and a sparse point cloud, dense reconstruction methods aim to create a complete 3D model with detailed surface information. Notable methods include:

1. **Multi-View Stereo (MVS)**: After obtaining camera poses through SfM, MVS algorithms like PMVS [8] generate dense point clouds by matching pixels across multiple images.
2. **Depth Map Fusion**: Methods such as COLMAP's MVS pipeline estimate per-image depth maps and then fuse them into a consistent 3D model.
3. **Neural Radiance Fields (NeRF)** [18]: A more recent approach that represents scenes as continuous 5D functions (spatial location and viewing direction) encoded in neural networks. NeRF takes camera poses from SfM as input and uses ray tracing to synthesize novel views with remarkable detail and view consistency.

Learning-based Reconstruction

Recent approaches leverage deep learning for 3D reconstruction, often using SfM-derived data for supervision or initialization:

1. **Learned MVS**: Methods like MVSNet [29] use convolutional neural networks to learn the depth estimation process directly from images and camera parameters.
2. **Single-view Reconstruction**: Networks like Mesh R-CNN [10] can estimate 3D structure from a single image by leveraging prior knowledge learned from large datasets.

2.1.3. Limitations of 3D Reconstruction

Structure from Motion is a powerful tool for 3D reconstruction, demonstrating high effectiveness across a variety of scenarios. However, it encounters significant challenges. These include dealing with textureless surfaces, reflective materials, and the computational

complexity of processing high-resolution images. Most importantly in the context of this thesis, it struggles with sparse input scenarios, such as those involving a single image or only a few images.

Traditional 3D reconstruction methods like SfM and MVS typically require a dense collection of images with sufficient overlap to establish accurate feature correspondences and camera pose estimations. When faced with limited input views—particularly in the extreme case of a single image—these methods often fail to generate complete and accurate 3D representations. The quality of reconstruction degrades significantly due to:

1. **Geometric ambiguity:** A single image or sparse set of images provides incomplete information about occluded regions and depth, leading to ambiguous geometry.
2. **Feature matching limitations:** Fewer images means fewer opportunities to establish reliable feature correspondences across different viewpoints.
3. **Inability to triangulate:** Robust triangulation requires features to be visible from multiple viewpoints, which is not possible with very limited inputs.
4. **View-dependent effects:** Materials with specular reflections or varying appearance based on viewpoint cannot be accurately modeled without multiple observations.

These limitations have motivated the development of generative approaches to novel view synthesis, particularly using diffusion models trained on large datasets of rendered images of 3D models. Instead of explicitly reconstructing geometry, these methods leverage the power of deep learning to hallucinate plausible views from unseen perspectives.

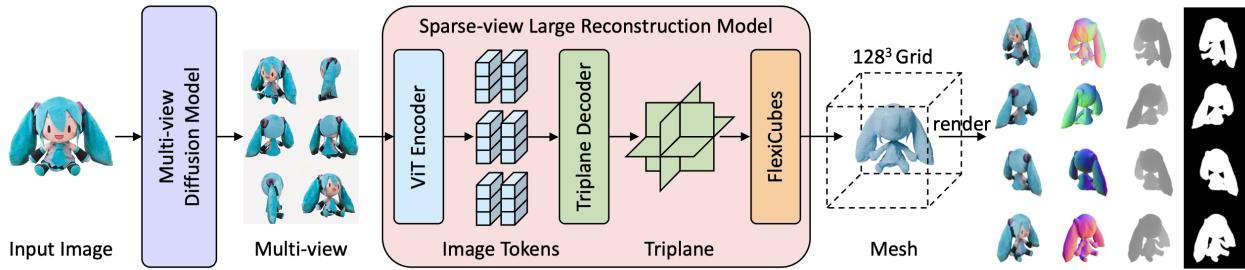


Figure 2.4: InstantMesh

Modern approaches of 3D object generation, such as InstantMesh [28], leverage these diffusion models to generate multiple consistent views of an object from minimal input (a single image or even a text prompt). This novel view synthesis is the first step in a pipeline 2.4 that can be used to create a 3D model of the object, and it is this particular step that forms the central focus of this thesis.

2.2. Deep Generative Models for Image Synthesis

The development of deep learning methods has led to remarkable progress in generative modeling, enabling the synthesis of highly realistic and diverse images. Among the various

approaches, Generative Adversarial Networks (GANs), Variational Autoencoders (VAEs), and Diffusion Models have emerged as the most prominent. While GANs and VAEs have laid significant groundwork and continue to be influential, this section will primarily focus on diffusion models, given their state-of-the-art performance in image quality and controllability, and their direct relevance to the multi-view synthesis tasks explored in this thesis.

2.2.1. Generative Adversarial Networks and Variational Autoencoders

Generative Adversarial Networks (GANs) [11] consist of two neural networks, a generator and a discriminator, trained in a competitive setting. The generator aims to produce realistic images, while the discriminator tries to distinguish between real images from the training dataset and fake images produced by the generator. Through this adversarial process, the generator learns to create increasingly plausible images. GANs are known for generating sharp images but often suffer from training instability.

Variational Autoencoders (VAEs) [14] are another class of generative models that learn a probabilistic mapping from a high-dimensional data space (e.g., images) to a lower-dimensional latent space, and then back to the data space. A VAE consists of an encoder that compresses the input data into a latent representation (typically a mean and variance defining a Gaussian distribution) and a decoder that reconstructs the data from samples drawn from this latent distribution. They are trained to maximize the evidence lower bound (ELBO), which involves a reconstruction loss and a regularization term (KL divergence) that encourages the latent space to be smooth and well-behaved. VAEs generally offer more stable training than GANs and can learn a meaningful latent space, but often produce slightly blurrier images. VAEs play a crucial role in the architecture of Latent Diffusion Models.

2.2.2. Diffusion Models

Diffusion models have recently become the dominant paradigm in high-fidelity image generation. They are inspired by non-equilibrium thermodynamics, specifically diffusion processes.

Core Concept: The Diffusion Process

The core idea behind diffusion models involves two processes: a forward (or diffusion) process and a reverse (or denoising) process. In the **forward process**, a known image x_0 from the dataset is gradually perturbed by adding small amounts of Gaussian noise over a sequence of T steps. This process progressively corrupts the image until, at step T , it becomes indistinguishable from pure isotropic Gaussian noise. The parameters of this noising process are fixed.

The **reverse process** aims to learn to reverse this noising. Starting from pure noise (equivalent to x_T), a neural network is trained to gradually denoise the signal, step-by-step, eventually producing a realistic image (an approximation of x_0). This learned denoising process is what allows the model to generate new images. Figure 2.5 illustrates this concept.

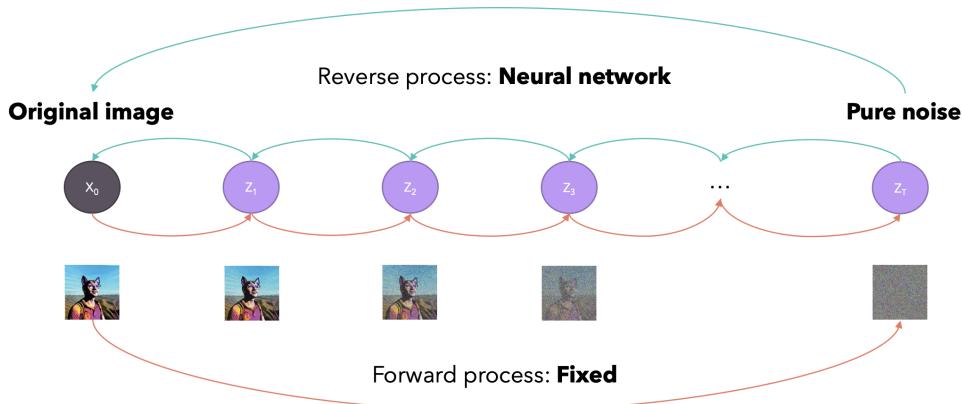


Figure 2.5: The forward (noising) and reverse (denoising/generation) stages of a diffusion model. The forward process gradually adds noise to an image until it becomes pure noise. The reverse process learned by a neural net to denoise, step-by-step, to generate an image from noise.

The U-Net Architecture

The neural network responsible for predicting the noise (or the denoised image) at each step in the reverse process is typically a U-Net architecture [23]. The U-Net, originally developed for biomedical image segmentation, features an encoder-decoder structure with skip (residual) connections. The encoder path progressively downsamples the input, capturing contextual information, while the decoder path progressively upsamples, localizing information. The skip connections concatenate features from the encoder to corresponding layers in the decoder, allowing the network to combine high-level semantic information with low-level detail, which is crucial for accurately predicting the noise and preserving image fidelity during the denoising steps.

Training Objective and Loss Function

The training objective of the diffusion model is to learn the conditional probability distribution $p_\theta(x_{t-1}|x_t)$, which represents the probability of the previous, less noisy state x_{t-1} given the current noisy state x_t . In practice, this is often simplified to training the U-Net to predict the noise ϵ that was added to an image x_0 to produce x_t at a given timestep t . The loss function is typically the Mean Squared Error (MSE) between the true added noise ϵ and the noise $\epsilon_\theta(x_t, t)$ predicted by the U-Net:

$$L = \mathbb{E}_{t \sim [1, T], x_0 \sim q(x_0), \epsilon \sim \mathcal{N}(0, I)} [\|\epsilon - \epsilon_\theta(x_t, t)\|^2]$$

where $x_t = \sqrt{\bar{\alpha}_t}x_0 + \sqrt{1 - \bar{\alpha}_t}\epsilon$, and $\bar{\alpha}_t$ are parameters from the noise schedule.

Conditional Generation: Text-to-Image Synthesis

To guide the image generation process, diffusion models can be conditioned on various inputs, most notably text prompts. This is the foundation of text-to-image synthesis. A

crucial component for text conditioning is a powerful text encoder that can convert textual descriptions into rich numerical representations (embeddings). Contrastive Language-Image Pre-training (CLIP) [21] is widely used for this purpose. CLIP is trained on a massive dataset of image-text pairs to learn a shared embedding space where semantically similar images and texts are close together.

The text embeddings from CLIP are then integrated into the U-Net, typically using cross-attention mechanisms. In these layers, the image representation at an intermediate layer of the U-Net queries the text embedding, allowing the model to align parts of the image with relevant words or phrases in the prompt. This enables fine-grained control over the generated image content based on the textual input.

2.2.3. Latent Diffusion Models (LDMs)

While standard diffusion models operate directly in the pixel space of images, this can be computationally very expensive, especially for high-resolution images, as the U-Net needs to process large tensors. Latent Diffusion Models (LDMs) [22], such as Stable Diffusion, address this challenge by performing the diffusion and denoising process in a lower-dimensional latent space.

LDMs employ a pre-trained autoencoder, typically a VAE. The VAE's encoder first compresses a high-resolution image from pixel space into a compact latent representation. The diffusion process (both forward and reverse) then occurs entirely within this latent space. Once the reverse denoising process generates a target latent representation from noise, the VAE's decoder maps this latent representation back into the high-resolution pixel space to produce the final image. Figure 2.6 depicts the architecture of an LDM.

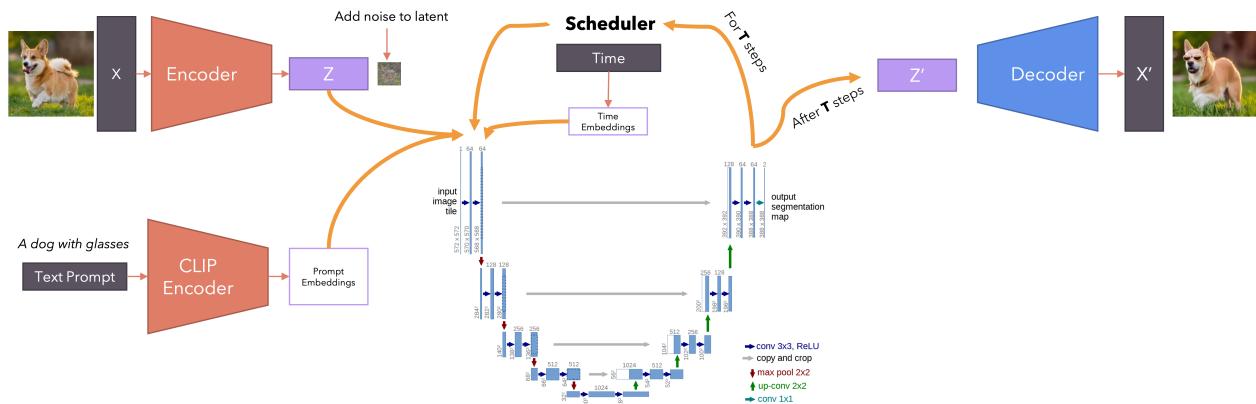


Figure 2.6: Architecture of a Latent Diffusion Model (LDM). An image is first encoded into a latent space by a VAE encoder. The diffusion process (noising and denoising via U-Net) occurs in this latent space. The generated latent is then decoded back to pixel space by the VAE decoder. Conditioning, such as text embeddings from CLIP, is incorporated into the U-Net.

By working in a compressed latent space, LDMs significantly reduce the computational burden during training and inference compared to pixel-space diffusion models. This makes it feasible to train powerful models on massive datasets and generate high-resolution images

more efficiently, without a substantial loss in quality. The VAE ensures that the latent space is perceptually equivalent to the pixel space, and the diffusion model learns to generate high-quality latents within this space.

2.3. Conditioning Diffusion Models for Enhanced Control and New Tasks

While textual prompts provide a powerful and intuitive way to guide diffusion models, the generation process can be conditioned on a much wider array of signals. This opens up possibilities for more fine-grained control over the output and enables new applications beyond text-to-image synthesis. This section explores several advanced conditioning mechanisms, focusing on image-based conditioning for detailed content and style control, and specialized techniques for incorporating geometric information, such as camera parameters, to enrich 2D diffusion models with 3D awareness.

2.3.1. Image-based Conditioning for Fine-Grained Control

Conditioning on reference images allows for precise control over spatial layout, object appearance, color consistency, or artistic style, going beyond what is often achievable with text alone.

ControlNet

ControlNet [32] introduces a method to add diverse spatial conditioning to pre-trained text-to-image diffusion models. Instead of fine-tuning the original large model, ControlNet involves training smaller, task-specific auxiliary networks that are attached to the frozen U-Net backbone of the diffusion model, typically to its encoder blocks. These auxiliary networks take an input conditioning image (e.g., an edge map, human pose skeleton, depth map, or segmentation map) and produce feature maps that are then added to the corresponding features of the main U-Net. This approach allows the pre-trained model to be guided by the spatial information in the conditioning image while retaining its vast generative capabilities learned from large datasets. The original U-Net weights are locked, making ControlNet modules efficient to train and portable. Figure 2.7 provides a conceptual overview.

IP-Adapter

IP-Adapter (Image Prompt Adapter) [30] offers an effective way to condition diffusion models using an image prompt, allowing the model to generate images that align with the content or style of the reference image. It achieves this by introducing a lightweight adapter module that can be plugged into a pre-trained text-to-image model. The core idea is to decouple the cross-attention mechanisms used for text and image features. Image features, extracted by an image encoder (like CLIP [21] image encoder), are fed into new cross-attention layers that work in parallel with the original text cross-attention layers. This allows the model to draw information from both text and image prompts simultaneously or prioritize one over

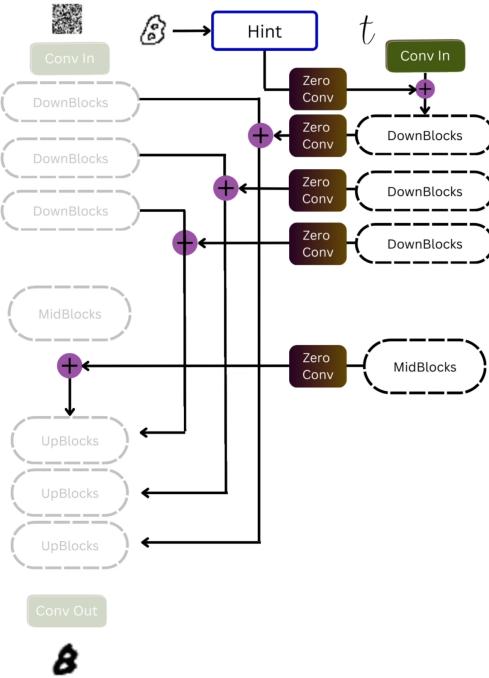


Figure 2.7: Conceptual overview of ControlNet, showing how an additional control module processes an input condition (e.g., edges, pose) and injects guidance into a pre-trained diffusion model. (Adapted from Zhang et al. [32])

the other. IP-Adapter is efficient as it avoids fine-tuning the large base model and only trains the adapter parameters, making it a versatile tool for tasks like style transfer or subject-driven generation. Figure 2.8 illustrates this concept.

CatVTON and UNet Feature Conditioning

A particularly relevant approach for image conditioning, especially for tasks requiring detailed transfer of appearance or garment characteristics, is found in methods like CatVTON [3]. The key insight in such methods is to leverage the rich, hierarchical features learned by the denoising U-Net itself. When provided with a reference image (e.g., an image of a specific garment), features can be extracted from various layers of the U-Net as it processes this reference. These extracted features, which encode information about texture, shape, and style at multiple scales, are then used to condition the generation of a new image (e.g., the same garment, but worn by a person). This conditioning can be achieved by injecting these features into the corresponding layers of the U-Net during the denoising process of the target image, often using attention mechanisms or direct feature fusion. This technique allows for a powerful form of image-based control that is highly attuned to the diffusion model's internal representations, facilitating tasks like virtual try-on with impressive fidelity by directly utilizing the U-Net's understanding of visual elements.

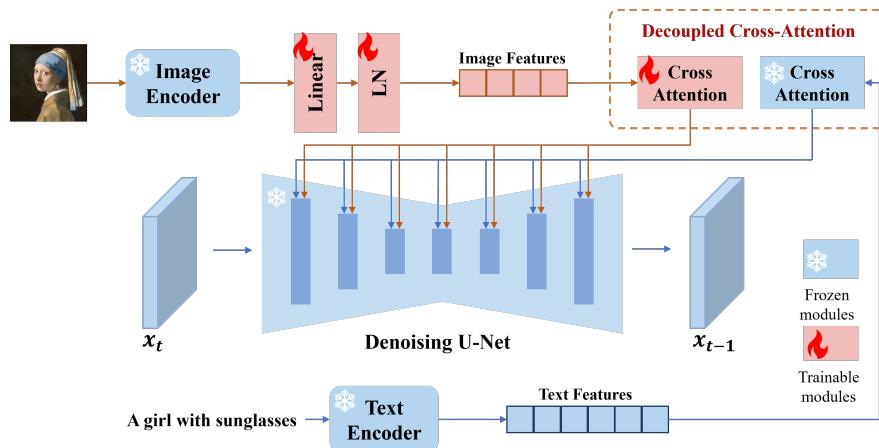


Figure 2.8: Conceptual illustration of the IP-Adapter architecture, showing how image features extracted by an image encoder are integrated into the U-Net via dedicated cross-attention layers to guide the generation process. (Image based on the IP-Adapter concept)

2.3.2. Modulating Network Activations

Feature-wise Linear Modulation (FiLM) [20] is a general and effective technique for conditioning neural network activations. Instead of directly concatenating conditioning information or using complex gating mechanisms, FiLM applies a simple affine transformation to feature maps based on a conditioning input. Given a feature map h from a layer in a neural network, and a conditioning vector c , a FiLM generator (typically a small neural network) produces a scale parameter γ and a shift parameter β from c . These parameters then modulate h as follows: $FiLM(h) = \gamma \cdot h + \beta$. This allows the conditioning information c to dynamically influence the behavior of the network layer by layer. FiLM is lightweight and can be integrated into various architectures to allow secondary inputs to control the processing of a primary input. Figure 2.9 illustrates the internals of a FiLM layer.

This approach enabled image-based models to effectively integrate and act upon conditioning information from outside the image domain. For instance, by modulating visual features based on encoded text tokens, it empowered (at the time) state-of-the-art image question answering models to ground their visual processing in textual context.

FiLMed-UNet

The FiLM technique has also been effectively applied to U-Net architectures in the medical imaging domain, notably in the FiLMed-UNet paper by Lemay et al. [15]. Their work focused on enhancing medical image segmentation by incorporating various forms of metadata as conditioning signals. FiLMed-UNet utilized patient-specific information, such as tumor type or the target organ for segmentation.

The core idea was to make the U-Net's segmentation process adaptable and more informed by this external metadata. The metadata (e.g., one-hot encoded tumor type) was passed through a FiLM generator network, which produced scale (γ) and shift (β) parameters. These parameters then modulated the feature maps at different layers within the U-Net. This allowed the network to tailor its feature extraction and segmentation logic based on the

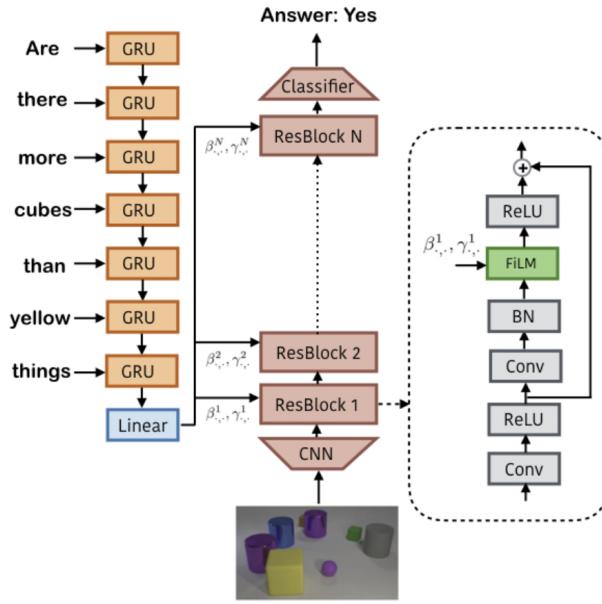


Figure 2.9: The Feature-wise Linear Modulation (FiLM) layer. A conditioning input is processed by a FiLM generator to produce scale (γ) and shift (β) parameters, which then modulate the feature maps (h) of a main network. (Adapted from Perez et al. [20])

provided metadata. For example, knowing the tumor type allowed the model to leverage type-specific visual characteristics, leading to improved segmentation accuracy. Furthermore, by conditioning on the desired output class (e.g., "segment kidney"), FiLMed-UNet demonstrated robustness in multi-task learning scenarios, even with missing labels for some tasks in the training data, and showed improved performance with limited annotations. While this application of FiLM is distinct from encoding camera parameters for 3D-aware synthesis, it highlights the versatility of FiLM in allowing neural networks to integrate and utilize diverse conditioning information to adapt their behavior for specialized tasks. Figure 2.10 shows a conceptual diagram.

2.3.3. Camera Parameter Encoding for 3D Awareness

Making 2D diffusion models inherently 3D-aware is crucial for tasks like multi-view image generation. A key aspect of this is encoding camera parameters (Rotation R , Translation t) to guide the image generation process. Various methods focus on integrating this geometric information directly into the model's input or intermediate representations.

Pixel-Level Geometric Conditioning: Ray-based Approaches

This category of methods aims to provide detailed, per-pixel geometric information derived from camera parameters directly to the diffusion model. A prominent technique is the use of a *raymap*, as demonstrated by Watson et al. [27] in 3DiM and also utilized in CAT3D [9]. The raymap is a tensor with the same spatial dimensions as the image or latent representation.

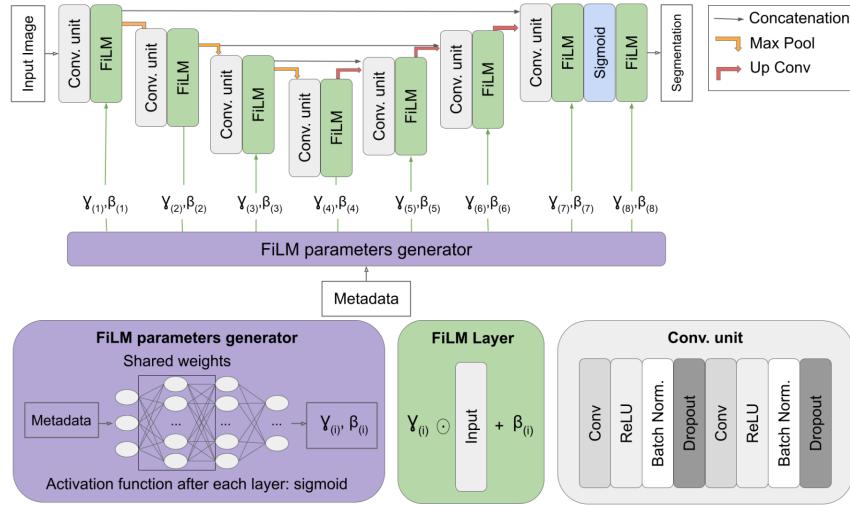


Figure 2.10: Conceptual diagram of a FiLMed-UNet. The metadata about patients are processed by a FiLM generator network, which outputs scale and shift parameters to modulate activations at various layers within the U-Net architecture, making the denoising process viewpoint-aware.

At each (u,v) coordinate, it stores the 3D origin and 3D direction of the camera ray passing through that pixel. In CAT3D, these rays are computed relative to the camera pose of the first conditional image. To help the network learn high-frequency details associated with viewpoint changes, these ray origins and directions are often further processed using positional encodings. The resulting positionally encoded raymap can be concatenated as an additional input channel to the U-Net, alongside the noisy image or latent representation [9, 27]. This allows the model to learn a direct, spatially varying mapping from ray geometry to the target pixel output.

Global Camera Pose Conditioning

Alongside per-pixel data, global camera pose conditioning methods provide a more compact, holistic representation of the camera's viewpoint or transformation. One approach involves *vectorized transformation embeddings*. For instance, Zero-1-to-3 [17] encodes the relative camera viewpoint transformation $T = [R|t]$ between an input view and a target view as a 4x4 matrix. This matrix is flattened into a 16-dimensional vector, which is then projected by a small Multi-Layer Perceptron (MLP) and added to the timestep embedding. This globally influences the diffusion process by providing context about the desired viewpoint change. Another technique employs *decomposed pose vectors for attention mechanisms*. MV-Adapter [13] represents each camera view using a 12-dimensional vector, which includes 3D camera coordinates and a 9D flattened rotation matrix. These vectors are processed by an MLP and then fed into multi-view attention layers as key and value components. This allows the model to explicitly attend to pose information when correlating features across different views, aiding in the generation of coherent multi-view imagery.

2.4. Diffusion-based Multi-View Image Generation

Building upon the camera parameter encoding techniques discussed in Section 2.3.3, this section delves into specific diffusion-based models and architectures designed for generating single or multiple consistent views of a 3D scene or objects. These methods aim to leverage the generative power of diffusion models to synthesize novel perspectives, often with the goal of creating coherent 3D representations.

2.4.1. Single Reference Image Novel View Synthesis

Novel View Synthesis (NVS) from a single reference image is a challenging task that several diffusion-based approaches have tackled.

Zero-1-to-3 [17], an early pioneer in this area, conditions a latent diffusion model on a single reference image and a relative camera pose transformation $T = [R|t]$ to generate a novel view. This model is fine-tuned from a pre-trained text-to-image model (Stable Diffusion). While demonstrating the potential for NVS without explicit 3D reconstruction, approaches like Zero-1-to-3 can sometimes face challenges in maintaining strong geometric consistency across widely varying generated views, a point often highlighted by subsequent multi-view generation methods [9, 26].

Concurrently, Watson et al. [27] proposed 3DiM, a diffusion model designed for NVS that operates in pixel space. It conditions on a single source RGB-D image (though it can function with RGB only) and an absolute target camera pose. 3DiM utilizes the raymap technique for camera conditioning, as detailed in Section 2.3.3, by constructing a raymap containing per-pixel 3D origin and direction, which is then positionally encoded and concatenated with the input image to the U-Net [27]. The model is trained to predict the clean target image from a noised source image.

2.4.2. Coherent Multi-View Generation Architectures

To improve consistency and enable robust 3D asset creation, several architectures focus on jointly generating or reasoning about multiple views simultaneously.

MVDream, often cited as a foundational multi-view model [9, 13, 26], extends diffusion models to generate multiple (e.g., four orthogonal) views from a shared text prompt by incorporating multi-view attention mechanisms. It learns from both 2D images and 3D assets to enhance 3D consistency [13].

Building on such concepts, ImageDream [26] introduces an image-prompt multi-view diffusion model. It takes a single image prompt and aims to generate multiple consistent views of an object. ImageDream leverages the canonical camera coordination (discussed in Section 2.3.3) established by MVDream, where a default camera view corresponds to the object's front view. Its key architectural contribution is a multi-level image-prompt controller that integrates image features at global (CLIP global embedding), local (CLIP hidden features), and pixel (VAE encoded image latent) levels into the MVDream-like diffusion U-Net [26]. The pixel controller, for instance, concatenates the input image prompt's latent as an additional frame to the four target views, enabling 3D self-attention across all five frames. ImageDream

employs Multi-View Score Distillation Sampling (MV-SDS) for reconstructing a NeRF from the generated views.

CAT3D [9] presents a multi-view diffusion model designed to simulate a real-world capture process by generating a large set of consistent novel views from one or more input images and specified target camera poses. Its architecture is similar to video latent diffusion models [2], employing 3D self-attention (2D in space and 1D corresponding to time across images) and is initialized from a pre-trained latent diffusion model. For camera conditioning, CAT3D uses the raymap approach (see Section 2.3.3), where ray origins and directions are computed relative to the first conditional image’s camera pose and concatenated channel-wise to the latents [9]. To generate a large number of views (e.g., 80 for single-image input, up to 960 for few-view), CAT3D can group target viewpoints and, for single-image inputs, may first autoregressively sample a set of anchor views before generating the remaining views. These generated views are then used as input to a robust 3D reconstruction pipeline (e.g., Zip-NeRF).

ViewCrafter [31], as noted by CAT3D [9], combines video latent diffusion models with 3D point cloud priors. This approach aims to achieve high-fidelity and consistent novel views by leveraging explicit 3D information alongside the generative capabilities of video diffusion models, enabling precise camera control.

While these architectures show impressive results, methods requiring full fine-tuning of large pre-trained models are expensive and may risk performance degradation if high-quality, large-scale 3D data for fine-tuning is scarce.

2.4.3. Specialized Multi-View Adapters

To mitigate the challenges of full fine-tuning, adapter-based methods offer a lightweight alternative for enabling pre-trained models with multi-view generation capabilities.

MV-Adapter [13] is a notable example, introducing a plug-and-play adapter for multi-view image generation that enhances pre-trained text-to-image diffusion models while preserving their original network structure and feature space. It employs a decoupled attention mechanism: the original spatial self-attention layers of the pre-trained model are kept frozen, and new multi-view attention layers are created by duplicating the structure and weights of these original layers. These new layers, organized in a parallel architecture, process features from multiple views (typically packed along the batch dimension) and learn geometric knowledge efficiently [13].

For encoding geometric information, MV-Adapter [13] integrates camera parameters using raymaps, an approach also seen in methods like 3DiM [27] and CAT3D [9]. These raymaps can be positionally encoded and are then typically supplied as additional input channels to the U-Net, processed by the adapter’s components. This method of providing direct geometric cues, combined with other conditioning signals like text or image embeddings processed through its attention mechanisms, allows for flexible control in tasks such as text-to-3D and image-to-3D generation. By updating significantly fewer parameters than full fine-tuning—primarily those of the adapter module—MV-Adapter enables efficient training, preserves the rich priors of the base model, and reduces the risk of overfitting.

3. Proposed Method TODO

In this chapter, I describe the proposed method.

3.1. Overview

3.2. Limitations of Previous Methods

Despite the significant progress in multi-view image generation and novel view synthesis, several limitations and research gaps remain:

1. **Computational Efficiency:** Full fine-tuning of diffusion models for multi-view generation is computationally expensive, especially when working with large base models and high-resolution images. While first adapter-based method MV-Adapter has improved efficiency of training, there is still room for improvement.
2. **Geometric Consistency:** Maintaining geometric consistency across generated views remains a challenge, particularly when generating views from significantly different perspectives. Current methods often struggle with complex occlusions, reflective surfaces and fine geometric details.
3. **Sparse Input Handling:** Most existing methods require either dense multi-view captures or make strong assumptions about the scene structure. There is a need for methods that can effectively handle sparse inputs (e.g., a single image or a few images) while generating high-quality novel views.
4. **Integration of Geometric Priors:** While some methods incorporate geometric information through camera poses or point clouds, the effective integration of these priors with generative models remains an open research question.

My work aims to address these limitations by developing a method that combines the efficiency of adapter-based approaches with the geometric consistency provided by point cloud priors. Specifically, I propose to extend the MV-Adapter framework by incorporating point cloud information as an additional conditioning signal, similar to the approach used in ControlNet. This will allow for more precise control over the generated views while maintaining the computational efficiency of adapter-based methods.

3.3. Multi-View Image Generation

3.4. Conditional Multi-View Image Generation

4. Data Preparation

In this chapter, I will discuss the datasets used in training the method presented in this thesis and the data augmentation techniques applied to them. The quality and nature of the data are paramount for training robust deep learning models, particularly for complex tasks such as novel view synthesis. This chapter details the meticulous process of curating and preparing the datasets used for training and validating the proposed method, with a primary focus on the extensive ObjaverseXL dataset used for training and the complementary Google Scanned Objects dataset used for validation.

4.1. Dataset Overview

Two primary datasets form the backbone of this work: ObjaverseXL, a large-scale repository of 3D models utilized for training the generative model, and Google Scanned Objects (GSO), a collection of high-fidelity 3D scans employed in my work for validation purposes.

4.1.1. ObjaverseXL: A Large-Scale 3D Model Repository

ObjaverseXL [5] is a vast, publicly accessible dataset comprising approximately 10 million 3D models. In order to use these models, one has to download them from their respective sources, which are often not straightforward. The models are stored in diverse online sources, including platforms like GitHub, Thingiverse, and Sketchfab, as shown in 4.1, resulting in a rich and varied collection that reflects a wide array of object categories, complexities, and artistic styles. Given its scale and diversity, ObjaverseXL serves as the primary source for the training data in this thesis.

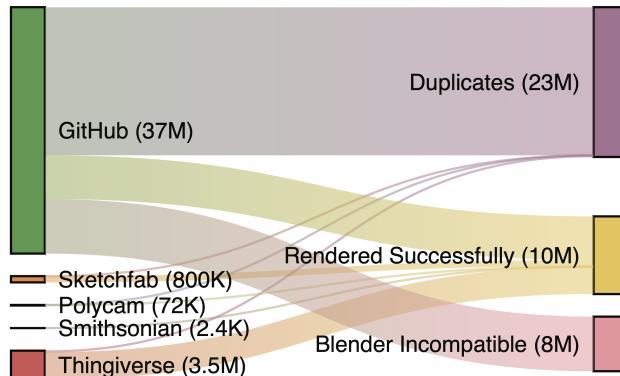


Figure 4.1: Illustrative overview of ObjaverseXL model sources and diversity.

4.1.2. Google Scanned Objects (GSO): High-Quality 3D Scans

The Google Scanned Objects (GSO) dataset [7] consists of high-fidelity 3D scans of real-world objects. In this work, the GSO dataset is utilized for the final validation of the trained multi-view image generation model. Its distinct origin and capture methodology compared to ObjaverseXL provide a benchmark for evaluating the generalization capabilities and output quality of the proposed method on unseen, high-quality data.

4.2. Processing Pipeline for ObjaverseXL Training Data

The transformation of raw 3D models from ObjaverseXL into a usable training dataset involved a comprehensive processing pipeline. This pipeline encompassed several critical stages: model acquisition, normalization, view rendering with specific lighting considerations, quality control filtering, and finally, textual annotation. Each step was carefully designed to address potential issues and ensure the final dataset's suitability for training an effective multi-view diffusion model.

4.2.1. 3D Model Acquisition and Initial Handling

The first step involved acquiring the 3D models from their respective sources as listed in the ObjaverseXL dataset. This task required scripting the download process due to the varied hosting platforms. The pipeline was designed to robustly handle common 3D model formats that typically support textures, including Object files (*.obj*), GLTF/GLB files (*.glb*, *.gltf*), Filmbox files (*.fbx*), and Collada files (*.dae*).

A critical part of initial handling was standardizing the coordinate system. 3D models from diverse origins often have different conventions for which axis represents "up". To ensure consistency, all imported mesh objects underwent a corrective rotation of -90 degrees around the X-axis. This transformation was immediately applied to the objects, establishing a common "Z-up" orientation for all models before subsequent processing steps. A preliminary inspection of model metadata was also performed upon successful download, which sometimes provided hints for orientation if the automated correction was insufficient, though the Z-up convention was paramount.

4.2.2. 3D Model Normalization and Scene Setup

To ensure consistency across all rendered images, a standardized scene setup was imperative. Each downloaded 3D model underwent a normalization process:

1. **Global Bounding Box Calculation:** The process began by calculating a single bounding box encompassing all mesh components of the loaded 3D model.
2. **Scaling to Unit Cube:** Based on the maximum dimension of this global bounding box, a uniform $scalefactor$ was determined. The model was then scaled by this factor to ensure it fit precisely within a 1x1x1 unit cube.

3. **Centering at Origin:** After scaling, the model was translated so that the center of its global bounding box was positioned at the world origin (0,0,0).

This normalization was critical for several reasons. Firstly, it ensured that objects, regardless of their original size, would fit within the camera's viewpoint. Secondly, it provided a consistent reference point for defining camera positions and distances, simplifying the multi-view rendering setup.

4.2.3. Multi-View Image Rendering

The core of the data generation process was rendering 2D images of each 3D model from multiple viewpoints.

Rendering Environment

All rendering tasks were performed using Blender [4], a powerful open-source 3D creation suite. To automate and scale the process, Blender was operated in windowless (headless) mode. The BLENDER_EEVEE rendering engine was chosen for its balance of speed and quality, making it suitable for generating a large volume of images. Render output was configured to 1024×1024 pixels in *PNG* format with *RGBA* color mode, enabling transparency. The background was explicitly set to transparent.

Specific EEVEE settings were configured to balance quality and performance while ensuring clear depiction of the objects:

- **Temporal Anti-Aliasing (TAA):** Render samples set to 32 for smoother edges.
- **Ambient Occlusion (GTAO):** Enabled to provide contact shadows and enhance perceived depth.
- **Bloom:** Disabled to prevent overly bright, glowing effects that could obscure object details.

Camera Viewpoint Configuration

Camera setup was designed for consistency and to provide a comprehensive view of the objects. Key camera parameters included:

- **Focal Length:** 35mm.
- **Sensor Width:** 32mm.
- **Camera Distance:** Cameras were positioned at a fixed distance of 1.8 Blender units from the world origin. Given the $1 \times 1 \times 1$ object normalization, this distance ensured the object was well-framed.
- **Targeting:** A *TRACKTO* constraint was applied to the camera, compelling it to always point towards the world origin (0,0,0), keeping the object centered.

To train a model capable of understanding objects from various perspectives and generalizing to different numbers of input views, images were rendered from a randomly selected set of predefined camera angles for each model. Three configurations were used for 6, 8 and 12 views, with specific azimuth (horizontal rotation) and elevation alternating between small positive and negative values to cover the object from all sides. The camera is focused on the origin. The placement is shown in 4.2 and 4.3.

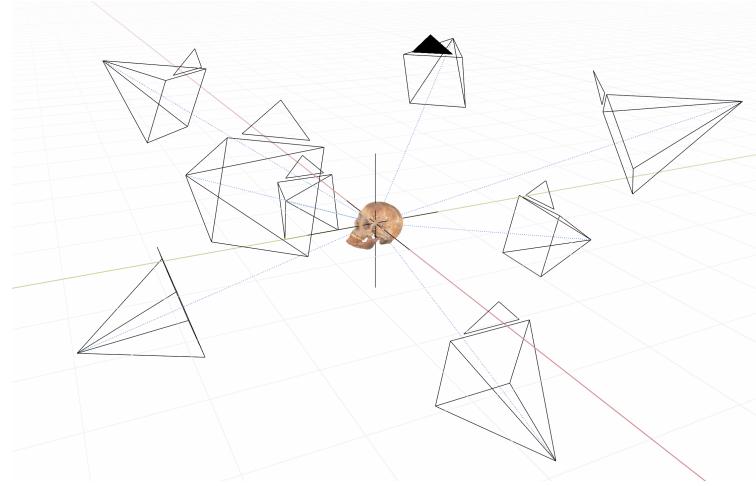


Figure 4.2: Example camera configurations for 8 views around an object.

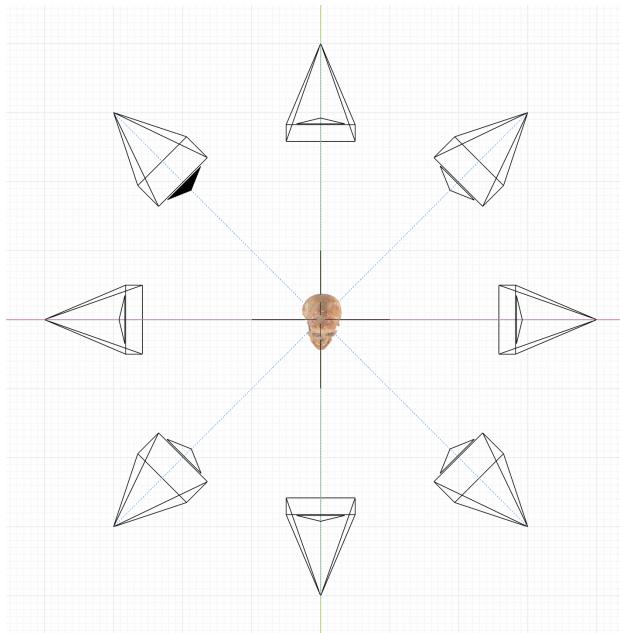


Figure 4.3: Camera configurations for 8 views around an object, visible from the top.

The choice of 6, 8, or 12 views for any given model was made randomly, with the dataset designed to have an approximately equal distribution of samples across these three groups. This strategy aimed to enhance the model's robustness to varying input view counts during

inference. Azimuth angles were defined to be counter-clockwise around the object to ensure compatibility with methods of 3D reconstruction like InstantMesh [28].

Lighting Strategy for Consistent Illumination

Lighting plays a critical role in the visual appearance of rendered objects. The example rendering scripts provided by the ObjaverseXL authors [6] employed a randomized lighting setup. While intended to introduce variability, this approach often resulted in images with harsh lighting, strong shadows, or scenes where the object was underexposed or even completely obscured because the light source was positioned unfavorably (e.g., behind the object relative to the camera). Such inconsistencies could negatively impact model training, potentially teaching the model to generate overly dark or inconsistently lit views.

To mitigate this, a revised, deterministic multi-point lighting strategy using four *SUN* type lights was adopted. The primary goal was to achieve soft, even illumination across the object’s surface, ensuring that its features were clearly visible from all rendered viewpoints.

The resulting images featured more consistently well-lit objects, reducing the likelihood of the diffusion model learning to arbitrarily darken parts of an object from perspectives different from the main light source direction in the input. This consistency is vital for learning accurate geometry and appearance.

4.2.4. Post-Rendering Quality Control and Filtering

Despite the controlled rendering setup, not all rendering attempts yielded high-quality images. Some 3D models were inherently problematic (e.g., incompatible formats, missing textures, non-manifold geometry), while others, due to their material properties or fine details, resulted in renders that provided little useful visual information (e.g., images consisting mainly of reflections, transparency artifacts, or indiscernible silhouettes). It was observed that approximately one-third of the initially rendered samples suffered from such quality issues.

To ensure the training data was of sufficient quality, a rigorous filtering process was implemented. This was based on a contrast score, calculated as the standard deviation of pixel intensities in the grayscale version of each rendered image. A minimum contrast threshold was established. If any of the rendered views for a particular 3D model fell below this threshold, the entire sample (the 3D model and all its associated renders) was discarded from the dataset. This strict approach ensured that only models with consistently clear and informative views were retained. After this filtering stage, approximately 20,000 high-quality 3D model samples, each with its set of 6, 8, or 12 views, remained.

4.2.5. Textual Prompt Generation via Multimodal LLM

To fine-tune a text-to-image diffusion model, rich textual descriptions (prompts) corresponding to the visual content are essential. Since the ObjaverseXL models do not inherently come with such descriptive prompts, they needed to be generated. For this task, a state-of-the-art multimodal Large Language Model (LLM), Qwen2.5VL [1], was employed. Qwen2.5VL is recognized for its strong performance in image description and visual question answering tasks.

The prompt generation process was as follows:

1. For each 3D model, three views were randomly selected from its set of successfully rendered and filtered images.
2. These three views were provided as parallel input to the Qwen2.5VL model.
3. The LLM was tasked with analyzing these views and generating a single, comprehensive, and descriptive text prompt that accurately captured the essence of the 3D object depicted.

This approach aimed to distill visual information from multiple perspectives into a rich textual description, providing effective conditioning for the diffusion model during training. The use of multiple views was intended to help the LLM form a more holistic understanding of the object compared to relying on a single view.

4.3. Processing of Google Scanned Objects (GSO) Validation Data

The Google Scanned Objects (GSO) dataset was processed with a similar pipeline to ensure consistency in evaluation. The primary steps involved:

1. Downloading the GSO 3D models.
2. Passing them through the same normalization, multi-view rendering (using the same camera configurations and lighting strategy), quality control filtering pipeline and textual prompt generation described in Section 4.2.

4.4. Final Dataset Characteristics

Following the comprehensive processing pipeline, the final datasets were prepared for model training and validation. The ObjaverseXL training dataset consists of approximately 20,000 unique 3D models, each associated with a set of high-quality rendered views (6, 8, or 12 per model) and a descriptive textual prompt generated by Qwen2.5VL. This curated dataset provides a rich and diverse source of multi-view image-text pairs for training the diffusion model.

The GSO validation dataset comprises a set of consistently rendered views from the high-fidelity GSO models (approximately 1000 models), ready to be used for evaluating the performance of the trained model, particularly its ability to generalize to unseen objects and maintain multi-view consistency. With these meticulously prepared datasets, the subsequent stages of model training and experimentation, as detailed in the following chapters, could proceed on a solid foundation.

5. Experiments TODO

In this chapter, I describe the experiments I conducted to evaluate the proposed method.

6. Results TODO

In this chapter, I present the results of the experiments.

7. Conclusions and Future Work TODO

Zakończenie, podsumowuje najważniejsze wnioski, podaje możliwości dalszego rozwinięcia wykonanych prac i wskazuje obszar potencjalnego zastosowania pracy. Rezultaty pracy mają charakter poznawczy, mogą mieć charakter użytkowy. Należy dokonać analizy uzyskanych wyników. Rezultaty powinny charakteryzować się oryginalnością, a nawet w pewnym stopniu nowatorstwem. Praca zawiera (...). Zostało pokazane (...). Eksperymenty wykazały (...). Tu piszemy wnioski i obserwacje.

Widzimy, że (...). Z tego powodu przyszła praca powinna obejmować (...).

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