UNREALZOO: ENRICHING PHOTO-REALISTIC VIRTUAL WORLDS FOR EMBODIED AI

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ABSTRACT

We introduce UnrealZoo [1], a rich collection of photo-realistic 3D virtual worlds built on Unreal Engine, designed to reflect the complexity and variability of the open worlds. Additionally, we offer a variety of playable entities for embodied AI agents. Based on UnrealCV, we provide a suite of easy-to-use Python APIs and tools for various potential applications, such as data collection, environment augmentation, distributed training, and benchmarking. We optimize the rendering and communication efficiency of UnrealCV to support advanced applications, such as multi-agent interaction. Our experiments benchmark agents in various complex scenes, focusing on visual navigation and tracking, which are fundamental capabilities for embodied visual intelligence. The results yield valuable insights into the advantages of diverse training environments for reinforcement learning (RL) agents and the challenges faced by current embodied vision agents, including those based on RL and large vision-language models (VLMs), in open worlds. These challenges involve latency in closed-loop control in dynamic scenes and reasoning about 3D spatial structures in unstructured terrain.

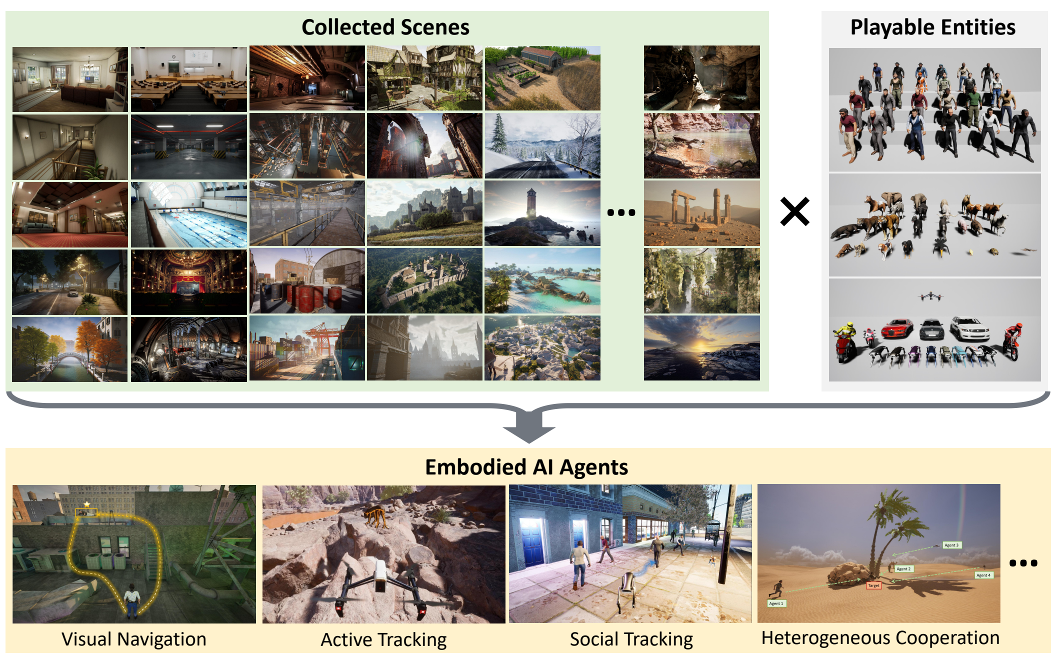

Figure 1: UnrealZoo enriches photo-realistic virtual worlds by combining diverse scenes and playable entities. It enables training generalizable embodied AI agents for tasks such as navigation, active tracking, and social interactions. Additionally, UnrealZoo facilitates the benchmarking of agents in realistic virtual worlds, helping to identify challenges in open-world deployments.

[1] Project page: http://unrealzoo.site/

1 INTRODUCTION

Currently, embodied artificial intelligence (Embodied AI) agents are often *homebodies*, primarily confined to controlled indoor environments and rarely venturing outside to explore the diversity of the open world. While several simulators (Kolve et al., 2017; Dosovitskiy et al., 2017; Puig et al., 2018; Li et al., 2023; Puig et al., 2024) have advanced the field, they often focus on specific scenarios, such as daily activities in homes or autonomous driving on urban roads. This narrow focus hinders AI agents' adaptability and generalization in diverse open worlds, e.g., industrial areas, public spaces, and natural landscapes, required by a wide range of real-world applications.

To bridge this gap, there is an increasing demand for simulators that feature a diverse range of open worlds. *First*, the diversity of the 3D scenes and bodies of agents is crucial to develop spatial intelligence (Davison, 2018), enabling agents to actively perceive, reason, plan, and act when handling numerous tasks in complex 3D worlds with varying dynamics and styles. *Second*, the complexity of multi-agent interactions is essential for developing social intelligence (Duéñez-Guzmán et al., 2023), such as the theory of mind (Jin et al., 2024), negotiation (Guan et al., 2024), cooperation (Wang et al., 2022), and competition (Zhong et al., 2021), encouraging agents to behave more like humans. *Third*, virtual worlds that mimic the challenges in open-world scenarios can evaluate agents efficiently and effectively, identifying limitations and preventing hardware losses from real-world deployment failures (Kadian et al., 2020). *Ultimately*, these features will inspire researchers to explore new challenges previously overlooked in other simulators (Duan et al., 2022), facilitating seamless integration into real-world applications.

In this work, we introduce UnrealZoo, a comprehensive collection of photo-realistic virtual worlds, based on Unreal Engine [2] and UnrealCV (Qiu et al., 2017). UnrealZoo features a diverse range of complex open worlds and playable entities to advance research in embodied AI and related domains. This high-quality set includes 100 realistic scenes at varying scales, such as houses, supermarkets, train stations, industrial factories, urban cities, villages, temples, and natural landscapes. Each environment is expertly designed by artists to mimic realistic lighting, textures, and dynamics, closely resembling real-world experiences. Our collection also includes diverse playable entities, including humans, animals, robots, drones, motorbikes, and cars. This diversity enables researchers to investigate the generalization of agents across different embodiments or build complex 3D social worlds with numerous heterogeneous agents. To enhance usability, we further optimize UnrealCV and offer a suite of easy-to-use Python APIs and tools (UnrealCV+), including environment augmentation, demonstration collection, and distributed training/testing. These tools allow for customization and extension of the environments to meet various needs in future applications, ensuring UnrealZoo remains adaptable as the embodied AI agents evolve.

We conduct experiments to demonstrate the applicability of UnrealZoo for embodied AI. First, we benchmark frames per second (FPS) across various commands, highlighting the significant improvement in image rendering and multi-agent interactions with the UnrealCV+ API. We use embodied visual navigation (Zhu et al., 2017) and tracking (Luo et al., 2018; Zhong et al., 2021) as two example tasks to benchmark embodied vision agents in complex dynamic environments with moving objects and unstructured maps. We also introduce a set of simple yet effective baseline methods for developing embodied vision agents, including distributed online reinforcement learning algorithms (Mnih et al., 2016), offline reinforcement learning algorithms (Kumar et al., 2020), and a reasoning framework for large vision-language models (VLMs). Our evaluations across different settings emphasize the importance of diverse training environments for enhancing agent generalization and robustness, the necessity of low latency in closed-loop control to handle dynamic factors, and the potential of reinforcement learning for training agents to navigate complex scenes.

Our contributions can be summarized in the following: 1) We build UnrealZoo, a collection of 100 high-quality photo-realistic scenes and a set of playable entities with diverse features, covering the most challenging to embodied AI agents in open worlds. 2) We optimize the communication efficiency of UnrealCV APIs and provide easy-to-use Gym interfaces with a toolkit for diverse requirements. 3) We conduct experiments to demonstrate the usability of UnrealZoo, showing the importance of the diversity of the environments to the embodied agents, and analyzing the limitations of the current RL-based and VLM-based agents in the open worlds.

[2] www.unrealengine.com

Table 1: The comparison with related photo-realistic virtual worlds for embodied AI. **Unstr. Terr.** indicates the presence of unstructured terrain. **Nav. Sys.** specifies whether the agent in the environment includes an autonomous navigation system. In Appendix A, we compare the visual realism across different engines in Figure 6 and list the descriptions of the symbols in Table 6.

Virtual Worlds	Scene: Categories	Scene: Scale Level	Scene: Style	Scene: Base Engine	Agent: Body	Agent: Nav. Sys.	Agent: Multi-agent
VirtualHome	🏠	Indoor	Modern, Western	Unity	🤵	✓	✓
AI2THOR	🏠	Indoor	Modern, Western	Unity	🤵🤖	-	-
ThreeDWorld	🏠🏘️⛰️	Indoor, Building, Community	Modern, Western, Nature	Unity	🤵🤖🛩️🚗	-	✓
OmniGibson	🏠	Indoor	Modern, Western	Omniverse	-	-	-
Habitat 3.0	🏠	Indoor	Modern, Western	Habitat-Sim	🤵🤖	✓	✓
CARLA	🛣️🏘️🏙️	Community, Landscape	Modern, Western, Nature	UE 4/5	🚗	✓	✓
AirSim	🛣️🏘️🏙️	Community, Landscape	Modern, Western, Nature	UE 4	🚗🛩️	-	✓
LEGENT	🏠🏡	Indoor, Building	Modern, Western	Unity	🤵🤖	✓	✓
V-IRL	🛣️🏙️	Community, Landscape	Modern, Western, Nature	Google Map	📷	✓	✓
UnrealZoo	🏠🏥🏟️🏪🛕 🏘️🏫🏭🚉🏰 🏙️🏝️⛰️🛣️🏞️	Indoor, Building, Community, Landscape	Ancient, Modern, Sci-Fi Western, Eastern, Nature	UE 4/5	🤵🤖🚗 🏍️🛩️📷 🐕🐎🐖	✓	✓

2 Related Works

Realistic Simulators for Embodied AI. Realistic simulators are extensively utilized in embodied artificial intelligence due to their appealing benefits, including high-quality rendering, cost-effective ground truth generation, low-cost interaction, and environmental controllability. They are crucial for training and testing AI agents to handle increasingly complex tasks. Notable realistic 3D simulators have been created for specific applications, such as indoor navigation (Kolve et al., 2017; Puig et al., 2018; Xia et al., 2018; Wu et al., 2018), robot manipulation (Yu et al., 2020; Ehsani et al., 2021; Chen et al., 2024), and autonomous driving (Gaidon et al., 2016; Shah et al., 2018; Dosovitskiy et al., 2017). Recent advances in computer graphics have spurred interest in developing general-purpose virtual worlds with photo-realistic rendering, allowing agents to collect high-fidelity data and learn skills applicable across various tasks and scenes. ThreeDWorlds (TDW) (Gan et al., 2021) and LEGENT (Cheng et al., 2024) are notable simulators that offer photo-realistic, multi-modal platforms, based on Unity, for interactive physical simulation. However, their built-in scenes and playable entities are somewhat limited. Additionally, the performance of the simulator decreases significantly in large outdoor environments, a typical weakness of Unity. V-IRL (Yang et al., 2024) is a recent approach that leverages Google Maps' API to simulate agents with real-world street view images, significantly reducing the gap between virtual and real-world settings. However, since V-IRL is inherently composed of static images, it lacks the capability to simulate the dynamics of the physical worlds for agent-object interactions. Recently, the community has also begun to explore dynamic environments with social interactions and unexpected events. However, existing solutions like Habitat 3.0 (Puig et al., 2024) focus on a limited number of agent interactions in indoor scenes, while HAZARD (Zhou et al., 2024b) addresses only single-agent simulations in dynamic scenarios like fires, floods, and winds. In contrast, UnrealZoo offers a comprehensive collection of scenes that feature various scenes at different scales, situations, eras, and cultural backgrounds with diverse playable entities for embodied AI. With advancements in Unreal Engine and optimized UnrealCV, our environment achieves real-time performance in large-scale scenes with multiple agents (around 10) and photo-realistic rendering. A comprehensive comparison across the related photo-realistic simulators is shown in Table 1.

Embodied Vision Agents. Embodied vision agents, which perceive and interact with their environments through vision, are a key focus in artificial intelligence research. These agents perform tasks like navigation (Zhu et al., 2017; Gupta et al., 2017; Yokoyama et al., 2024; Long et al., 2024), active object tracking (Luo et al., 2018; Zhong et al., 2019; 2021; 2023; 2024), and other interactive tasks (Chaplot et al., 2020; Weihs et al., 2021; Ci et al., 2023; Wang et al., 2023), mimicking human behavior. Their development involves various methods, including state representation learning (Yadav et al., 2023; Yuan et al., 2022; Gadre et al., 2022; Yang et al., 2023), reinforcement learning (RL) (Schulman et al., 2017; Xu et al., 2024; Ma et al., 2024), and large vision-language models (VLMs) (Zhang et al., 2024; Zhou et al., 2024a). Despite significant progress, challenges remain. RL methods often require extensive trial-and-error interactions and computational resources for training, and they usually struggle to generalize to new environments. Conversely, VLM-based methods excel at interpreting language instructions and images but may lack the fine-grained control and adaptability necessary for real-time interactions. The computational demands and time needed for inference with

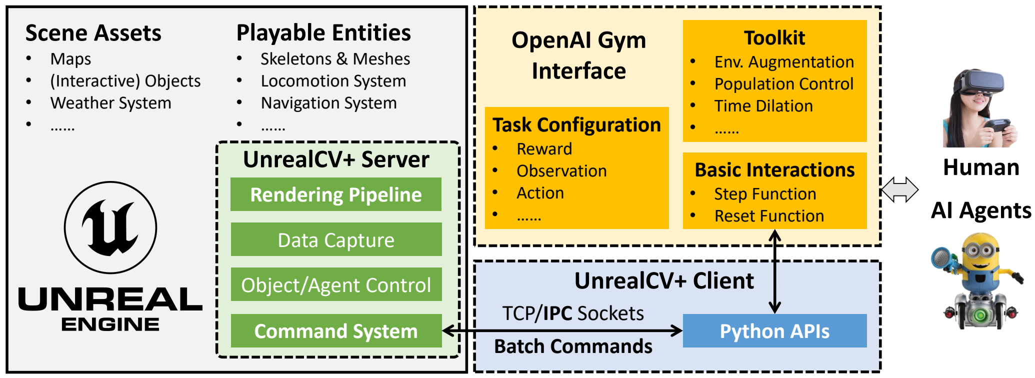

Figure 2: The detailed architecture of UnrealZoo. The Gray box indicates the UE binary, collecting the scenes and playable entities. The UnrealCV+ Server is built in the binary as a plugin. We have bolded the names of the optimized or new modules in UnrealCV+ Server and Client. We provide OpenAI Gym Interfaces for agent-environment interaction, which has been widely used in the community. Our gym interface supports customizing the task in a configuration file and contains a toolkit with a set of gym wrappers for environment augmentation, population control, etc.

such large models are critical, especially in dynamic scenes. Moreover, previous simulators mainly focus on indoor rooms or urban roads, which mask the potential challenges to the embodied agents when deploying in open worlds, e.g., unstructured terrain, dynamic changing factors, inference costs of the perception-control loop, and social interactions with other agents. Therefore, it is required to benchmark agents in large-scale, photo-realistic open worlds, taking into account various real-world challenges in the virtual worlds. In this work, we collect a subset of environments from UnrealZoo and benchmark embodied visual navigation and tracking agents, to emphasize the weakness of the existing RL-based and VLM-based methods.

3 UnrealZoo

UnrealZoo is a collection of photo-realistic, interactive open-world environments with diverse embodied characters, built on Unreal Engine and UnrealCV (Qiu et al., 2017). The environments are sourced from the *Unreal Engine Marketplace* [3], which shares high-quality content from artists, and were accumulated over two years at a cost exceeding $10,000$. UnrealZoo features a diverse array of scenes with varying sizes and styles. Among them, the largest scene, i.e., Medieval Nature Environment, covers more than $16km^2$ areas. The environments also include a wide range of embodiment, such as human avatars, vehicles, drones, animals, and virtual cameras, all of which can interact with the environment and equipped with ego-centric sensing systems. We offer easy-to-use Python APIs based on UnrealCV to facilitate interaction between Python programs and the game engine. Note that UnrealCV is optimized for rendering and communication, particularly in large-scale and multi-agent scenarios, namely UnrealCV+. Additionally, we provide OpenAI Gym interfaces to standardize agent-environment interactions. The gym-like interface also contains a set of toolkits, e.g., environment augmentation, population control, time dilation, and JSON-style task configurations to help the user customize the environments for various tasks with minimal effort.

3.1 Scene Collection

UnrealCV Zoo contains 100 scenes based on Unreal Engine 4 and 5. We select the scene based on the public reviews in the marketplace and the difference between the collected scenes, aiming at covering a wide range of styles from ancient to fictional, ensuring diversity. We provide an overview of the environments in the scene gallery.

We have tagged the collected scenes with several feature labels allowing researchers to select appropriate scenes for testing or training based on the tags associated with each scene. Our tags cover the following aspects:

[3] https://www.unrealengine.com/marketplace

- **Scene Categories**: We categorize scenes into three main types: interior, exterior, and both. The interiors include private houses, museums, supermarkets, train stations, factories, gyms, and caves. The exteriors include various outdoor terrains such as ruins, islands, plazas, neighborhoods, and mountains. Additionally, there are 46 scenes that include both interior and exterior elements, offering a blend of architectural elements and natural landscapes, enhancing the versatility and realism of our collection. More details about the distribution of the scenes are shown in Figure 7.
- **Scale**: Each scene is labeled according to its scale, and categorized into four levels: indoor, building, community, and landscape. The indoor scale is the smallest, typically encompassing one or multiple interior rooms (up to a complete floor), such as apartments and office interiors. The building scale includes a single building and its immediate surroundings, like a museum, supermarket, or gas station. The community scale covers areas with multiple buildings, such as neighborhoods, villages, castles, or container yards. The landscape scale includes vast natural or man-made areas, or parts of a city or an entire small town, such as mountains, forests, islands, and urban districts. Specifically, there are 35 scenes classified as landscape, 28 as community, 23 as building, and 15 as indoor. The largest scene covers 16 square kilometers.
- **Spatial Structure**: We also tag the spatial structure of the scenes, including multi-floor, topological, flat, steep, etc. Such categorization is vital for benchmarking the spatial intelligence of embodied agents. Multi-floor structures, for instance, challenge agents with vertical navigation and require advanced path-planning algorithms. Topological features, such as interconnected pathways, test the agent's ability to understand and traverse complex networks.
- **Dynamics**: The environment's dynamics include simulating factors like weather, fire, gas, fluid, and interactive objects. These elements enhance the visual and physical diversity of the scene while evaluating agents' adaptability and generalization. Weather variations such as sandstorms, snowfall, and thunderstorms are crucial, as are interactive objects like doors that agents can interact with. These dynamics are vital for an open-world experience.
- **Style**: The scenes may also represent diverse styles that reflect various cultures and eras, such as *Asian Temple*, *Western Church*, and *Middle Eastern Street*. Cultural labels include *Western*, *Asian*, and *Middle Eastern*, while era labels encompass *Medieval*, *Modern*, and *Science Fiction*. Identifying the styles will help us build a new data set to benchmark how social agents adapt to different backgrounds.

After categorizing the scenes, we integrate UnrealCV+ (Refer to Section 3.3) into the UE project and add the controllable player assets (Refer to Section 3.2) to each scene. Due to licensing restrictions, content purchased from the marketplace cannot be open-source, so we package the projects into an executable binary for sharing with the community. These executable binaries will be compatible with various operating systems, including Windows, Linux, and macOS, allowing users to download and run them via the Python interface without needing any knowledge of Unreal Engine, which is primarily built on C++ and Blueprint.

3.2 Playable Entities

UnrealZoo includes seven types of playable entities: humans, animals, cars, motorbikes, drones, mobile robots, and flying cameras (See Figure 1). Specifically, it comprises 19 human entities, 27 animal entities (dog, horse, elephant, pig, bird, turtle, etc), 3 cars, 14 quadruped robots, 3 motorcycles, and 1 quad-copter drone. This diversity, with varying affordances like action space and viewpoint, allows us to explore new challenges in embodied AI, such as cross-embodiment generalization and heterogeneous multi-agent interactions.

Each entity includes a skeleton with appropriate meshes and textures, a local motion system, and a navigation system. We offer a set of callable functions for each entity, enabling users to modify attributes like size, appearance, and camera positions, as well as control movements. Each entity can switch between different textures and appearances via UnrealCV API, enhancing visual diversity and adaptability for various scenarios. Each entity is equipped with an ego-centric camera, allowing the users to capture various types of image data such as RGB, depth, surface normal, and instance-level segmentation (object mask) from the agent's ego-centric view. Figure 3 shows examples of the captured first-person view and third-person view images of different entities with varying locomotion. For multi-agent interaction, the population of the entities in a scene can be easily adjusted using the spawn or destroy functions.

The locomotion system is built on Smart Locomotion, a well-designed and smooth locomotion system. It contains a number of high-quality animations that enable the agent to interact with the scene, such as opening and closing doors, crouching under obstacles, jumping over obstacles, climbing onto a platform, and simulating injury or death. With the locomotion system, we can explore the agent's ability to reason, plan, and interact in large-scale complex 3D scenes in advance, ignoring learning skills for low-level action control that requires high-fidelity physical simulation.

The navigation system is built on NavMesh allowing agents to autonomously navigate with the built-in AI controller. This includes path-finding and obstacle-avoidance capabilities, ensuring smooth and realistic movement throughout diverse terrains and structures. For urban-style maps, we segment the roads to distinguish between pedestrian and vehicle pathways. When agents use the navigation system for autonomous control, they will navigate the shortest path based on the priority of the different areas. For example, pedestrians and animals will prioritize walking on sidewalks, while vehicles and motorcycles will prioritize driving on roadways. An example of the navigation area is shown in Figure 10.

3.3 Programming Interface

We provide UnrealCV+ as the basic application programming interface (API) on Python to capture data and control the entities and scenes, and provide an OpenAI Gym interface for general agent-environment interactions. The architectures of the programming interfaces are shown in Figure 2.

UnrealCV+ is our improved version of the UnrealCV (Qiu et al., 2017) for high-throughput interactions. As the original version of UrnealCV primarily focuses on generating synthesis data for computer vision, the frame rates per second (FPS) are not optimized for real-time interactions. We optimize the rendering pipelines in the UnrealCV server and the communication protocols between the server and the client to improve the FPS. Specifically, we enable parallel processing while rendering object masks and depth images, which can significantly improve the FPS in large-scale scenes. For multi-agent interactions, we further introduce the batch commands protocol. In this protocol, the client can simultaneously send a batch of commands to the server, processing all the received commands and returning a batch of results. In this way, we can reduce the time spent on server-client communication. Since reinforcement learning requires extensive trial-and-error interactions for training, often running multiple environments on a computer, we introduce Inter-process communication (IPC) sockets instead of TCP sockets to improve the stability of the server-client communication under high loads. We benchmark the FPS performance in Table 2. To enhance user-friendliness, we have developed high-level Python APIs that are built upon the command systems of UnrealCV. These APIs encapsulate all the request commands and their corresponding data decoders into a callable Python function. This approach significantly simplifies the process for beginners, allowing them to interact with and customize the environment using UnrealCV+.

Gym Interface is used to define the interactive tasks and standardize the agent-environment interaction, following Gym-UnrealCV. Even though there are a lot of tasks for agents, they usually share common interaction protocols, i.e., the agent gets observations from the environment and returns actions. The main difference across different tasks usually is the reward functions, the modality of the

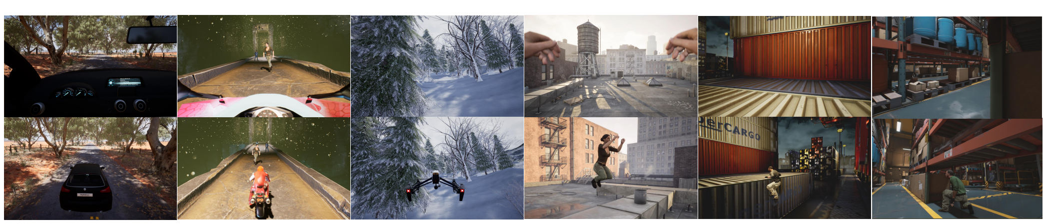

Figure 3: First-person (Top) and third-person (Bottom) view images of different entities in different scenes. Note that camera parameters can be reconfigured by UnrealCV APIs.

Table 2: Comparison of FPS in Unreal Engine 4.27 with UnrealCV and UnrealCV+. The reported result is an average performance across 6 typical environments.

	Image Capture				Multi-agent Interaction		
	Color	Object Mask	Surface Normal	Depth	N=2	N=6	N=10
UnrealCV	74	70	109	52	35	13	8
UnrealCV+	83($\uparrow$ 12%)	154($\uparrow$ 120%)	131($\uparrow$ 20%)	97($\uparrow$ 86%)	54($\uparrow$ 54%)	25($\uparrow$ 92%)	16($\uparrow$ 100%)

observation, and the available actions. Hence, we define the basic interaction functions for general usage and list the task-specific configurations, e.g., scene name, and reward function, in a JSON File, as shown in Figure 12. In this way, when adding new UE scenes, the users only need to set the parameters in the JSON files. Moreover, we contain a toolkit with a set of gym wrappers for training and testing the agents, such as environment augmentation that has been in previous work for training generalizable agents (Luo et al., 2018; 2020), population control to adjust the number of agents in the scene, and time dilation to adjust the control frequency in dynamic scenes. In Section 4.3, we demonstrate an example usage of the toolkit to analyze the robustness of social tracking agents to the population of crowds and the impact of the control frequency in such dynamic scenes. We also provide a launch tool to enable the user to run multiple environments with specific GPU IDs within a computer, which is useful for distributed online reinforcement learning (Ci et al., 2023).

4 Experiments

In this section, we use a subset of UnrealZoo to demonstrate the usability of the collected environments. For visual navigation, we select two scenes with complex spatial structures to train and validate the RL-based and VLM-based agents. For active tracking, we select at most 8 scenes as training environments and validate the generalization of the learned policy in another 24 scenes, which are divided into four categories according to the scene types. The results demonstrate the importance of the diversity of the training environments to the cross-domain generalization. For social tracking, we analyze the robustness of the agent in social environments with different control frequencies, using the toolkit provided in the gym to generate crowds with varying populations and control frequencies.

4.1 Visual Navigation

visual navigation in the wild introduces a new level of complexity compared to traditional navigation tasks for indoor scenes or autonomous driving, which often run on complex 3D spatial structures. Differently, we place the agent in open-world environments where it must take a set of locomotion, e.g., running, climbing, jumping, crouching, to go over the various obstacles in unstructured terrains to reach the target object. In this setting, the agent requires advanced spatial reasoning and actions to make real-time decisions about its path. The emphasis on such complex environments ensures the agent can operate effectively in a broad range of challenging scenarios, moving beyond the constraints of traditional navigation frameworks. The details of the task setting are introduced in Appendix B.1.

Evaluation Metrics. We employ two key metrics to evaluate visual navigation agents: 1) Average Episode Length (EL), representing the average number of steps per episode over 50 episodes. 2) Success Rate (SR), measuring the percentage of episodes the agent successfully navigates to the target object out of 50 total episodes, which represents the navigation capability in the wild environment.

Baselines for Navigation. We build simple baselines to demonstrate the applicability of our environments for training reinforcement learning agents and benchmark the agents based on pre-trained large models. **1) Online RL**: We trained the RL-based navigation agents separately in the Roof and Factory environments using a distributed online reinforcement learning (RL) approach, e.g. A3C (Mnih et al., 2016). The training curve is shown in Figure 16. The model takes the first-person view segmentation mask and the relative position between the agent and target as input, and outputs direct control signals (from the predefined action space) to navigate. This setup allows the agent to learn and optimize navigation strategies during continuous interaction with the environment. Please refer to Appendix C.1 for the implementation details. **2) GPT-4o**: We employ the GPT-4o model to take action, leveraging its powerful multi-modal reasoning capabilities. The model takes first-person view images and the relative position between the agent and the fixed target as input. The GPT-4o model follows our prompt template (See Table 14) as guidance, reasoning appropriate actions from the predefined control space to guide the agent toward the target. **3) Human**: We also have a human player control the agent using a keyboard, similar to a first-person video game. The player navigates

Figure 4: An exemplar sequence from the embodied navigation agent in the *Roof*. The RL-based agent learned to climb on a box and wall and jump over an obstacle to reach the goal location in a short path.

the agent from a random starting point to a fixed target, making decisions based on visual observations from the shared control space.

Results. In Table 3, we report the performances of different methods in two unstructured scenes. The RL-based agent performs moderately well, achieving better results in the simpler environment (*IndustrialArea*) compared to the *Roof*, where the target object is located on different levels of stairs. The GPT-4o agent struggles in both scenarios. This infers that the GPT-4o performs poorly in complex 3D scene reasoning. As a reference, the human player completes both tasks with the fewest steps and a 1.00 success rate, underscoring the significant performance gap between current embodied AI agents and humans, indicating substantial room for improvement to navigate in such complex, open-world environments.

4.2 Active Visual Tracking

We evaluate the generalization of the tracking agents across four environment categories: **Interior Scenes**, **Palaces**, **Wilds**, and **Modern Scenes**. Each category contains 4 individual environments, as shown in Figure 9. We aim to capture a broad range of features in our environment collection by selecting four distinct and representative scenes from each category, ensuring a comprehensive evaluation of the agents' capabilities. The details of the tasks are introduced in Appendix B.2. We analyzed the effectiveness of the diversity of the training data by collecting demonstrations with different numbers of training environments.

Table 3: The results (EL/SR) of visual navigation in two unstructured terrains.

Methods	Roof	IndustrialArea
Online RL	1660/0.32	261/0.52
GPT-4o	2000/0.00	369/0.20
Human	515/1.00	158/1.00

Evaluation Metrics. Our evaluation employs three key metrics: (1) Average Episodic Return (ER), which calculates the mean episodic return over 50 episodes, providing insights into overall tracking performance; (2) Average Episode Length (EL), representing the average number of steps per episode, which reflects long-term tracking effectiveness; and (3) Success Rate (SR), measuring the percentage of episodes that complete 500 steps out of 50 total episodes.

Baselines for Active Visual Tracking. For the *RL-based agents*, we extend from the official implementation settings from the recent offline RL method (Zhong et al., 2024), collecting offline datasets and employing the original network architecture. To demonstrate the impact of data diversity on tracking performance, we collect three sets of offline datasets, each containing 100k steps. The key difference between these datasets is the number of environments used for data collection: one was collected in a single environment (denoted as *1 Env.*), another in two environments(denoted as *2 Envs.*), and the third in eight distinct environments (denoted as *8 Envs.*). The offline training curve of each setting is shown in Figure 15. The environment distribution of each dataset setting is shown in Figure 11. It is worth noting that FlexibleRoom, one of the environments used for data collection, is a unique abstract environment, with all objects represented as geometric shapes covered by randomized patterns. This distinctive setup contrasts with the more realistic and diverse environments in the collection, offering a unique scenario for testing agent adaptability. For the *VLM-based agents*, we utilize the latest large models GPT-4o to directly generate actions based on observed images for tracking a target person. To ensure smooth and precise transitions, we designed a system prompt that helps the model understand the task while standardizing the output format to align with predefined action settings. This prompt ensures the model produces actions coherent with the task's requirements. Specifically, GPT-4o is tasked with generating concrete action decisions from a predefined instruction space: moving forward, moving backward, turning left, turning right, or maintaining the current position. Once an instruction is generated, we map it to corresponding linear and angular velocities to update the agent's movement in the environment. It is important to note that while the system prompt can use raw image observations as input, our experience shows poor alignment performance and significant time delays, which pose challenges for real-time tracking. The full system prompt and mapping relationship are provided in Appendix C.2.

Result Analysis. We first evaluate the performance of agents trained with offline datasets collected from varying numbers of environments (1 Env., 2 Envs., 8 Envs.) across **16 distinct environments**. We list the detailed evaluation results across the entire 16 environments in Table 11. To better visualize the performance change of different training settings within various scene categories, we calculate the average success rate (SR) of each agent in four categories, the results are shown in Figure 5. The results reveal a clear trend: **as the number of environments used for training increases, agent long-term tracking performance generally improves across all categories.** In the Wilds, a significant increase in success rate is observed with the 8 Envs. dataset, which involves the highest diversity of environments. This demonstrates that diverse environmental exposure plays a crucial role in improving the agent's generalization capabilities in more complex, open-world environments. The lower success rate in the 1 Env. dataset highlights the limitations of training solely in abstract settings like the FlexibleRoom. Similarly, in the Palace, the success rate improves notably from 1 Env. to 8 Envs., suggesting that training with a broader range of environments helps the agent better adapt to intricate spatial structures typical of Palace-like maze environments.

4.3 Social Tracking

We further evaluate the tracking agents in a social scenario, where the agent needs to follow the target in crowds. Such a setting contains varying high-dynamics objects with similar appearances, e.g., pedestrians. We can directly apply the population control wrapper in the Gym toolkit to extend the environment used for active tracking to this setting.

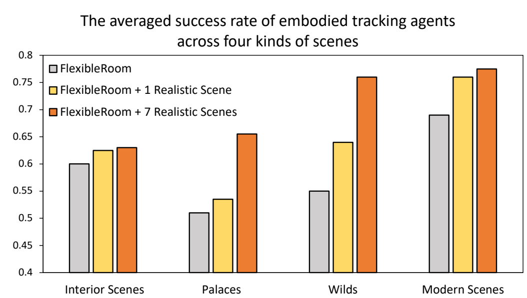

Figure 5: Average success rate of agents across four environment categories: Compact Interior, Wildscape Realm, Palace Maze, and Lifelike Urbanity, evaluated under three offline dataset settings (1 Env, 2 Envs., 8 Envs.). The results show the generalization capability improves significantly as more diverse environments are included in the dataset. However, environments with complex spatial structures, such as Compact Interior and Palace Maze, exhibit lower success rates, highlighting challenges in obstacle avoidance and navigation.

Robustness to Active Distractions. A key challenge in active visual tracking tasks is managing active distractions, a critical issue for real-world deployment in crowds. Thus, we conducted an experiment in the *DowntownWest* and generated crowds with varying numbers of human characters as distractors notated as 4D, 8D, and 10D. The number indicates the number of distractors. We compared the performance of the offline RL method, trained under three dataset configurations (1 Env., 2 Envs., 8 Envs.), against the VLM-based method, evaluating the agents' ability to maintain robust tracking under these different levels of active distractions.

The results in Table 5 show clear performance differences between the offline RL methods (1 Env., 2 Envs., 8 Envs.) and the GPT-4o model in handling active distractions. As the number of distractors increases, the offline RL methods maintain relatively stable success rates (SR), with the highest performance seen in the 8 Envs. setting, which achieves an SR of 0.8 in the 4D condition and remains robust with slight declines in the 8D and 10D conditions (0.72 and 0.68, respectively). This suggests that the agent benefits from the richer diversity of training data, enabling it to handle increasingly complex crowd scenarios more effectively. On the other hand, the GPT-4o model consistently struggles with active distractions, showing significantly

Table 5: Performance comparison of different methods in the DowntownWest environment with varying numbers of distractors (4D, 8D, 10D). Each cell presents three metrics from left to right: Average Episodic Return (ER), Average Episode Length (EL), and Success Rate (SR).

Method	4D	8D	10D
Offline RL 1 Env.	251/450/0.70	201/406/0.58	230/247/0.64
Offline RL 2 Envs.	309/456/0.74	259/424/0.68	258/428/0.68
Offline RL 8 Envs.	245/458/0.80	225/435/0.72	218/444/0.68
Offline RL 8 Envs. (Robot dog)	220/409/0.48	189/386/0.42	143/367/0.40
GPT-4o	-102/264/0.16	-64/270/0.14	-80/240/0.10

lower average returns (ER) and success rates across all settings. The model's inability to cope with dynamic, crowded environments is evidenced by its poor performance, particularly in the 10D condition where it records a success rate of just 0.1. This highlights a major limitation of the VLM-based method in dynamic environments with active distractions, as it lacks the temporal consistency and real-time adaptability required for effective tracking. Further evaluation results across different environments are provided in the Appendix D.3.

Cross-Embodiment Generalization. We transfer the agent trained for the human character to the robot dog, which observes the world from a lower perspective. We can see that the results in Table 5 drop, particularly the success rate, indicating that the research community should pay more attention to the cross-embodiment generalization.

The Impact of Control Frequency. We employ the time dilation wrapper to simulate different control frequencies during deployment. The frequency of the perception-control loop is crucial for handling dynamic environments. As is shown in Table 4, when the rate drops below 10 FPS, performance significantly declines. We observe that higher control frequencies enable RL-based agents to perform better in social tracking. These results emphasize the importance of building efficient models for embodied agents, to accomplish tasks in dynamic open worlds.

4.4 Limitation Analysis and Summary

The current RL method shows some capacity to learn spatial-temporal information and dynamically respond to target movement in most scenarios, but it struggles with executing advanced actions like bypassing obstacles. In compact Interior categories and some special environments such as TerrainDemo, IndustrialArea, and ModularSciFiSeason1, which feature irregular landscapes, narrow passageways, and maze-like structures, the agent often collides with casually placed low-level objects. While the agent can track targets, it's insufficient to handle unpredictable hindrances, especially in key moments like bypassing corners or tight spaces, which increases the likelihood of failure. This highlights a significant limitation: although the agent can learn and react to its environment, it lacks the higher-level reasoning to anticipate and avoid obstacles effectively. Advanced behaviors like bypassing obstacles are crucial for improving performance, especially in cluttered environments where basic reactive controls are insufficient. Incorporating such reasoning mechanisms would help reduce failure rates, particularly in critical scenarios, and improve overall tracking performance.

Table 4: The impact of control frequency on tracking performance. We evaluate the agent (Offline RL 1 Env.) in the FlexibleRoom environment using the time dilation wrapper to simulate varying control frequencies.

	ER/ EL/ SR.
3 FPS	184/377/0.34
10 FPS	303/449/0.62
30 FPS	368/482/0.92
w/o Control	275/425/0.74

For the VLM-based method, one key factor contributing to GPT-4o's notably poor performance, especially in comparison to the RL methods, is its susceptibility to time delays. From our experience, this issue becomes particularly evident when the target makes abrupt movements, such as turning around. Due to the API's response lag, the GPT-4o agent struggles to track the target in real time, often losing it before receiving updated instructions. This limitation highlights the difficulty of real-time processing in embodied tracking tasks using models that rely on slower external API communications, underscoring the need for more efficient integration methods for such systems.

5 CONCLUSIONS

In conclusion, we present UnrealZoo, a versatile platform designed to advance embodied AI research. The diversity and complexity of the collected realistic environments challenge agents with varying embodied interaction tasks, such as visual navigation, active tracking across various environments, and social tracking in crowds. The enhanced UnrealCV+ API supports efficient data collection and task customization, enabling seamless interaction for both single and multi-agent systems. These features will open up potential applications like developing spatial intelligence in the 3D world and social intelligence in human-AI society, making our platform a valuable tool for pushing the boundaries of embodied AI in real-world scenarios. Looking forward, we will continue to enrich the virtual worlds with diverse scenes, bodies, and interaction tasks, advancing agents from the virtual realm to reality for a harmonious human-AI society.

Limitations. While our proposed environment provides diverse and complex scenarios for visual navigation, tracking, and other visual-based tasks, it currently lacks high-fidelity physical simulation, limiting the agent's ability to manipulate objects. Additionally, transferring learned behaviors to different embodied agents poses a challenge, as adapting models to various physical structures and control schemes is not yet seamless. These issues highlight areas for further research to enhance interaction dynamics and improve generalization across diverse agent embodiments.

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REFERENCES

Devendra Singh Chaplot, Dhiraj Gandhi, Saurabh Gupta, Abhinav Gupta, and Ruslan Salakhutdinov. Learning to explore using active neural slam. In *International Conference on Learning Representations*, 2020. URL `https://openreview.net/forum?id=HklXn1BKDH`.

Yuanpei Chen, Yiran Geng, Fangwei Zhong, Jiaming Ji, Jiechuang Jiang, Zongqing Lu, Hao Dong, and Yaodong Yang. Bi-dexhands: Towards human-level bimanual dexterous manipulation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 46(5):2804–2818, 2024. doi: 10.1109/TPAMI.2023.3339515.

Zhili Cheng, Zhitong Wang, Jinyi Hu, Shengding Hu, An Liu, Yuge Tu, Pengkai Li, Lei Shi, Zhiyuan Liu, and Maosong Sun. Legent: Open platform for embodied agents. *arXiv preprint arXiv:2404.18243*, 2024.

Hai Ci, Mickel Liu, Xuehai Pan, Fangwei Zhong, and Yizhou Wang. Proactive multi-camera collaboration for 3d human pose estimation. In *The Eleventh International Conference on Learning Representations*, 2023. URL `https://openreview.net/forum?id=CPIy9TWFYBG`.

Andrew J Davison. Futuremapping: The computational structure of spatial ai systems. *arXiv preprint arXiv:1803.11288*, 2018.

Alexey Dosovitskiy, German Ros, Felipe Codevilla, Antonio Lopez, and Vladlen Koltun. Carla: An open urban driving simulator. In *Conference on Robot Learning*, pp. 1–16. PMLR, 2017.

Jiafei Duan, Samson Yu, Hui Li Tan, Hongyuan Zhu, and Cheston Tan. A survey of embodied ai: From simulators to research tasks. *IEEE Transactions on Emerging Topics in Computational Intelligence*, 6(2):230–244, 2022.

Edgar A Duéñez-Guzmán, Suzanne Sadedin, Jane X Wang, Kevin R McKee, and Joel Z Leibo. A social path to human-like artificial intelligence. *Nature Machine Intelligence*, 5(11):1181–1188, 2023.

Kiana Ehsani, Winson Han, Alvaro Herrasti, Eli VanderBilt, Luca Weihs, Eric Kolve, Aniruddha Kembhavi, and Roozbeh Mottaghi. Manipulathor: A framework for visual object manipulation. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 4497–4506, 2021.

Samir Yitzhak Gadre, Kiana Ehsani, Shuran Song, and Roozbeh Mottaghi. Continuous scene representations for embodied ai. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 14849–14859, 2022.

Adrien Gaidon, Qiao Wang, Yohann Cabon, and Eleonora Vig. Virtual worlds as proxy for multi-object tracking analysis. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 4340–4349, 2016.

Chuang Gan, Jeremy Schwartz, Seth Alter, Damian Mrowca, Martin Schrimpf, James Traer, Julian De Freitas, Jonas Kubilius, Abhishek Bhandwaldar, Nick Haber, Megumi Sano, Kuno Kim, Elias Wang, Michael Lingelbach, Aidan Curtis, Kevin Tyler Feigelis, Daniel Bear, Dan Gutfreund, David Daniel Cox, Antonio Torralba, James J. DiCarlo, Joshua B. Tenenbaum, Josh Mcdermott, and Daniel LK Yamins. ThreeDWorld: A platform for interactive multi-modal physical simulation. In *Thirty-fifth Conference on Neural Information Processing Systems Datasets and Benchmarks Track*, 2021. URL `https://openreview.net/forum?id=db1InWAwW2T`.

Zhenyu Guan, Xiangyu Kong, Fangwei Zhong, and Yizhou Wang. Richelieu: Self-evolving LLM-based agents for AI diplomacy. In *The Thirty-eighth Annual Conference on Neural Information Processing Systems*, 2024. URL `https://openreview.net/forum?id=7Jb4NJS8Yk`.

Saurabh Gupta, James Davidson, Sergey Levine, Rahul Sukthankar, and Jitendra Malik. Cognitive mapping and planning for visual navigation. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 2616–2625, 2017.

Chuanyang Jin, Yutong Wu, Jing Cao, Jiannan Xiang, Yen-Ling Kuo, Zhiting Hu, Tomer Ullman, Antonio Torralba, Joshua Tenenbaum, and Tianmin Shu. MMToM-QA: Multimodal theory of mind question answering. In *Proceedings of the 62nd Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pp. 16077–16102, 2024.

Abhishek Kadian, Joanne Truong, Aaron Gokaslan, Alexander Clegg, Erik Wijmans, Stefan Lee, Manolis Savva, Sonia Chernova, and Dhruv Batra. Sim2real predictivity: Does evaluation in simulation predict real-world performance? *IEEE Robotics and Automation Letters*, 5(4):6670–6677, 2020.

Eric Kolve, Roozbeh Mottaghi, Winson Han, Eli VanderBilt, Luca Weihs, Alvaro Herrasti, Matt Deitke, Kiana Ehsani, Daniel Gordon, Yuke Zhu, et al. AI2-THOR: An interactive 3d environment for visual ai. *arXiv preprint arXiv:1712.05474*, 2017.

Aviral Kumar, Aurick Zhou, George Tucker, and Sergey Levine. Conservative q-learning for offline reinforcement learning. *Advances in Neural Information Processing Systems*, 33:1179–1191, 2020.

Chengshu Li, Ruohan Zhang, Josiah Wong, Cem Gokmen, Sanjana Srivastava, Roberto Martín-Martín, Chen Wang, Gabrael Levine, Michael Lingelbach, Jiankai Sun, et al. Behavior-1k: A benchmark for embodied ai with 1,000 everyday activities and realistic simulation. In *Conference on Robot Learning*, pp. 80–93. PMLR, 2023.

Yuxing Long, Wenzhe Cai, Hongcheng Wang, Guanqi Zhan, and Hao Dong. Instructnav: Zero-shot system for generic instruction navigation in unexplored environment. In *8th Annual Conference on Robot Learning*, 2024. URL `https://openreview.net/forum?id=fCDOfpTCzZ`.

Wenhan Luo, Peng Sun, Fangwei Zhong, Wei Liu, Tong Zhang, and Yizhou Wang. End-to-end active object tracking via reinforcement learning. In *International Conference on Machine Learning*, pp. 3286–3295. PMLR, 2018.

Wenhan Luo, Peng Sun, Fangwei Zhong, Wei Liu, Tong Zhang, and Yizhou Wang. End-to-end active object tracking and its real-world deployment via reinforcement learning. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 42(6):1317–1332, 2020. doi: 10.1109/TPAMI.2019.2899570.

Guozheng Ma, Lu Li, Sen Zhang, Zixuan Liu, Zhen Wang, Yixin Chen, Li Shen, Xueqian Wang, and Dacheng Tao. Revisiting plasticity in visual reinforcement learning: Data, modules and training stages. In *The Twelfth International Conference on Learning Representations*, 2024. URL `https://openreview.net/forum?id=0aR1s9YxoL`.

Volodymyr Mnih, Adria Puigdomenech Badia, Mehdi Mirza, Alex Graves, Timothy Lillicrap, Tim Harley, David Silver, and Koray Kavukcuoglu. Asynchronous methods for deep reinforcement learning. In *International Conference on Machine Learning*, pp. 1928–1937, 2016.

Xavier Puig, Kevin Ra, Marko Boben, Jiaman Li, Tingwu Wang, Sanja Fidler, and Antonio Torralba. Virtualhome: Simulating household activities via programs. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 8494–8502, 2018.

Xavier Puig, Eric Undersander, Andrew Szot, Mikael Dallaire Cote, Tsung-Yen Yang, Ruslan Partsey, Ruta Desai, Alexander Clegg, Michal Hlavac, So Yeon Min, Vladimír Vondruš, Theophile Gervet, Vincent-Pierre Berges, John M Turner, Oleksandr Maksymets, Zsolt Kira, Mrinal Kalakrishnan, Jitendra Malik, Devendra Singh Chaplot, Unnat Jain, Dhruv Batra, Akshara Rai, and Roozbeh Mottaghi. Habitat 3.0: A co-habitat for humans, avatars, and robots. In *The Twelfth International Conference on Learning Representations*, 2024. URL `https://openreview.net/forum?id=4znwzG92CE`.

Weichao Qiu, Fangwei Zhong, Yi Zhang, Siyuan Qiao, Zihao Xiao, Tae Soo Kim, and Yizhou Wang. Unrealcv: Virtual worlds for computer vision. In *Proceedings of the 25th ACM International Conference on Multimedia*, pp. 1221–1224, 2017.

John Schulman, Filip Wolski, Prafulla Dhariwal, Alec Radford, and Oleg Klimov. Proximal policy optimization algorithms. *arXiv preprint arXiv:1707.06347*, 2017.

Shital Shah, Debadeepta Dey, Chris Lovett, and Ashish Kapoor. Airsim: High-fidelity visual and physical simulation for autonomous vehicles. In *Field and Service Robotics*, pp. 621–635, 2018.

Weiqi Wang, Zihang Zhao, Ziyuan Jiao, Yixin Zhu, Song-Chun Zhu, and Hangxin Liu. Rearrange indoor scenes for human-robot co-activity. In *2023 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 11943–11949. IEEE, 2023.

Yuanfei Wang, fangwei zhong, Jing Xu, and Yizhou Wang. Tom2c: Target-oriented multi-agent communication and cooperation with theory of mind. In *International Conference on Learning Representations*, 2022. URL `https://openreview.net/forum?id=2t7CkQXNpuq`.

Luca Weihs, Matt Deitke, Aniruddha Kembhavi, and Roozbeh Mottaghi. Visual room rearrangement. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 5922–5931, 2021.

Yi Wu, Yuxin Wu, Georgia Gkioxari, and Yuandong Tian. Building generalizable agents with a realistic and rich 3d environment. *arXiv preprint arXiv:1801.02209*, 2018.

Fei Xia, Amir R Zamir, Zhiyang He, Alexander Sax, Jitendra Malik, and Silvio Savarese. Gibson env: Real-world perception for embodied agents. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 9068–9079, 2018.

Guowei Xu, Ruijie Zheng, Yongyuan Liang, Xiyao Wang, Zhecheng Yuan, Tianying Ji, Yu Luo, Xiaoyu Liu, Jiaxin Yuan, Pu Hua, Shuzhen Li, Yanjie Ze, Hal Daumé III, Furong Huang, and Huazhe Xu. Drm: Mastering visual reinforcement learning through dormant ratio minimization. In *The Twelfth International Conference on Learning Representations*, 2024. URL `https://openreview.net/forum?id=MSe8YFbhUE`.

Karmesh Yadav, Ram Ramrakhya, Arjun Majumdar, Vincent-Pierre Berges, Sachit Kuhar, Dhruv Batra, Alexei Baevski, and Oleksandr Maksymets. Offline visual representation learning for embodied navigation. In *Workshop on Reincarnating Reinforcement Learning at ICLR 2023*, 2023.

Jihan Yang, Runyu Ding, Ellis Brown, Xiaojuan Qi, and Saining Xie. V-irl: Grounding virtual intelligence in real life. *arXiv preprint arXiv:2402.03310*, 2024.

Jinyu Yang, Mingqi Gao, Zhe Li, Shang Gao, Fangjing Wang, and Feng Zheng. Track anything: Segment anything meets videos. *arXiv preprint arXiv:2304.11968*, 2023.

Naoki Yokoyama, Sehoon Ha, Dhruv Batra, Jiuguang Wang, and Bernadette Bucher. Vlfm: Vision-language frontier maps for zero-shot semantic navigation. In *International Conference on Robotics and Automation (ICRA)*, 2024.

Tianhe Yu, Deirdre Quillen, Zhanpeng He, Ryan Julian, Karol Hausman, Chelsea Finn, and Sergey Levine. Meta-world: A benchmark and evaluation for multi-task and meta reinforcement learning. In *Conference on Robot Learning*, pp. 1094–1100. PMLR, 2020.

Zhecheng Yuan, Zhengrong Xue, Bo Yuan, Xueqian Wang, Yi Wu, Yang Gao, and Huazhe Xu. Pre-trained image encoder for generalizable visual reinforcement learning. In *Advances in Neural Information Processing Systems*, volume 35, pp. 13022–13037, 2022.

Jiazhao Zhang, Kunyu Wang, Rongtao Xu, Gengze Zhou, Yicong Hong, Xiaomeng Fang, Qi Wu, Zhizheng Zhang, and Wang He. Navid: Video-based vlm plans the next step for vision-and-language navigation. *arXiv preprint arXiv:2402.15852*, 2024.

Fangwei Zhong, Peng Sun, Wenhan Luo, Tingyun Yan, and Yizhou Wang. AD-VAT: An asymmetric dueling mechanism for learning visual active tracking. In *International Conference on Learning Representations*, 2019. URL `https://openreview.net/forum?id=HkgYmhR9KX`.

Fangwei Zhong, Peng Sun, Wenhan Luo, Tingyun Yan, and Yizhou Wang. Towards distraction-robust active visual tracking. In *International Conference on Machine Learning*, pp. 12782–12792. PMLR, 2021.

Fangwei Zhong, Xiao Bi, Yudi Zhang, Wei Zhang, and Yizhou Wang. Rspt: reconstruct surroundings and predict trajectory for generalizable active object tracking. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 37, pp. 3705–3714, 2023.

Fangwei Zhong, Kui Wu, Hai Ci, Churan Wang, and Hao Chen. Empowering embodied visual tracking with visual foundation models and offline rl. In *European Conference on Computer Vision*, pp. 139–155. Springer, 2024.

Gengze Zhou, Yicong Hong, and Qi Wu. Navgpt: Explicit reasoning in vision-and-language navigation with large language models. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 38, pp. 7641–7649, 2024a.

Qinhong Zhou, Sunli Chen, Yisong Wang, Haozhe Xu, Weihua Du, Hongxin Zhang, Yilun Du, Joshua B. Tenenbaum, and Chuang Gan. HAZARD challenge: Embodied decision making in dynamically changing environments. In *The Twelfth International Conference on Learning Representations*, 2024b. URL `https://openreview.net/forum?id=n6mLhaBahJ`.

Yuke Zhu, Roozbeh Mottaghi, Eric Kolve, Joseph J. Lim, Abhinav Gupta, Li Fei-Fei, and Ali Farhadi. Target-driven visual navigation in indoor scenes using deep reinforcement learning. In *International Conference on Robotics and Automation (ICRA)*, 2017.

A UE ENVIRONMENTS

A.1 COMPARISON WITH OTHER SIMULATORS

To better explain Table 1, we list the description of each symbol about the scene types and playable entities in Table 6. Since photorealism mainly relies on the engine used, we visualize the snapshots rendered by different engines in Figure 6. Note that Google Maps are images captured in the real world, but can not simulate the dynamic of the scenes and interactions between objects. By utilizing advanced rendering and physics engines, Unreal Engine simulates large-scale photorealistic environments that are not only visually appealing but also capable of complex interactions between agents and objects. So we choose to build environments on Unreal Engine.

Table 6: The description of symbols used in Table 1.

Symbol	**Description**
🏠	Interior house with furnishings
🏘	Residential community with multiple buildings
🏙	High-fidelity large-scale urban environments
🛣	Exterior scenes with roads
⛰	Natural scenes with forests or grasslands
🏞	Large-scale natural landscape, including lakes, mountains, desert
🏝	An island landscape
🏰	Castle-style historic buildings
🛕	Asian temple architecture features stairs, lofts, and shrines.
🏭	Industrial areas with internal roads and factory facilities
🏫	Educational settings, including classrooms and gymnasiums.
🏟	Sports venue scenes, such as swimming pool, sport stadium.
🏪	Supermarket contains a wide range of daily essentials and produce.
🚉	Typical urban public transportation hubs, such as train and gas stations.
🏥	Detailed hospital interior scenes.
🤵	Human characters with detailed features such as hair textures, clothing, and actions
🤖	Mobile robot
🚗	Driveable car
🐕 🐎 🐖	Animals include common animal species such as cats, dogs, horses, pigs, etc.
🏍	Driveable motorbike
🛩	Drones
📷	Virtual camera that has no physical entity and is movable

A.2 ENVIRONMENTS USED IN VISUAL NAVIGATION

We carefully selected two photo-realistic environments (**Roof** and **Factory**) for training and evaluating navigation in the wild, shown in Figure 8. The Roof environment features multiple levels connected by staircases and large pipelines scattered on the ground, providing an ideal setting for the agent to learn complex action combinations for transitioning between levels, such as jumping, climbing, and navigating around obstacles. The Factory environment, on the other hand, is characterized by compact boxes and narrow pathways, challenging the agent to determine the appropriate moments to jump over obstacles or crouch to navigate under them. These two environments offer diverse spatial structures, enabling agents to develop an understanding of multi-level transitions and precise obstacle avoidance.

A.3 ENVIRONMENTS USED IN ACTIVE VISUAL TRACKING

For training agents via offline reinforcement learning, we selected 8 distinct environments to collect demonstrations, as is shown in Figure 11. To comprehensively evaluate the generalization of the active visual tracking agents, we selected **16** distinct environments, categorized into Interior Scenes, Palaces, Wilds, and Modern Scenes. Each category presents unique challenges: 1) **Interior Scenes** feature complex indoor structures with frequent obstacles; 2) **Palaces** include multi-level structures and narrow pathways; 3) **Wilds** encompass irregular terrain and varying illumination; 4) **Modern**

Figure 6: Comparison of the visual realism of different engines: we show the snapshots captured from different engines to compare the photo-realism of different environments for an intuitive feeling. Note that Google Maps capture and reconstruct the images from the real world, but can not simulate the dynamic of the scenes and interactions between agents and objects.

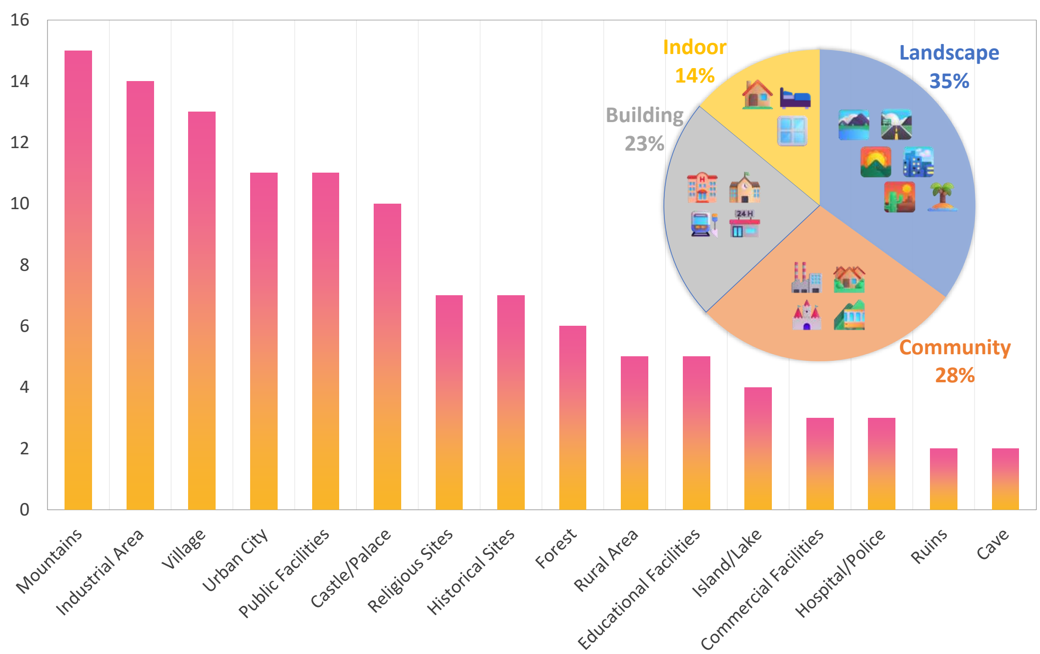

Figure 7: The statistical distribution of scene content and scale in UnrealZoo. The bar chart depicts the number of scenarios featuring each type of content, noting that larger scenes may encompass multiple categories. The pie chart classifies these scenes by scale, revealing a predominance of large-scale 'Landscape' environments, followed by 'Community', 'Building', and 'Indoor' levels. The distribution reflects the diversity of UnrealZoo and the balanced composition of scenes of different scales.

Scenes offer high-fidelity, real-world scenarios with modern buildings and objects. These diverse environments facilitate a thorough assessment of the agent's generalization capabilities across varying complexities. The snapshot of each environment is shown in Figure 9.

Figure 8: Two photo-realistic environments used for visual navigation.

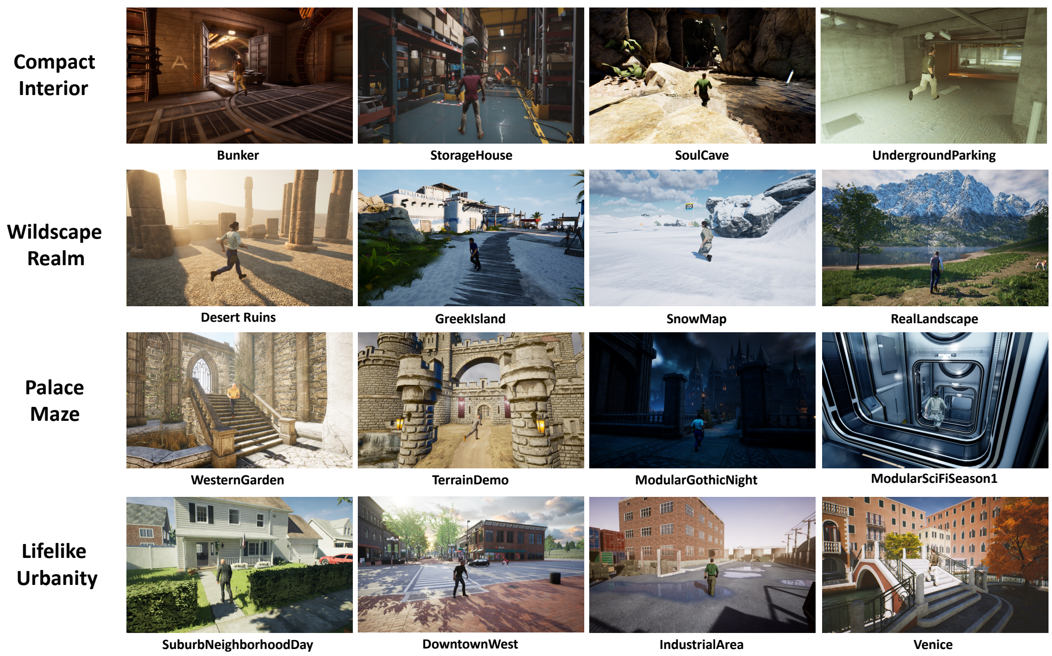

Figure 9: The snapshots of 16 environments used for testing active visual tracking agents. The text on the left indicates the category corresponding to that line of environment.

A.4 Navigation Mesh

Based on NavMesh, we build an internal navigation system, allowing agents to autonomously navigate with the built-in AI controller in the Unreal Engine. This includes path-finding and obstacle-avoidance capabilities, ensuring smooth and realistic movement throughout diverse terrains and structures. Moreover, in our City style map, we manually construct road segmentation, we manually segment the roads to distinguish between pedestrian and vehicle pathways. When agents use the navigation system for autonomous control, they will navigate the shortest path based on the priority of the different areas. Figure 10 shows an example of the rendered semantic segmentation for NavMesh in an urban city.

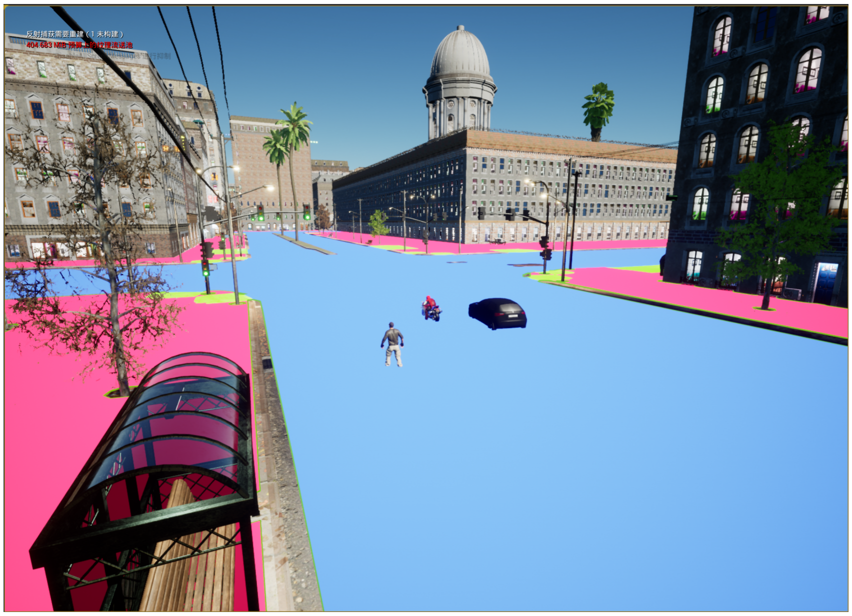

Figure 10: An example of the NavMesh with semantic segmentation. The human character will prioritize using the pink area for pedestrian navigation tasks, while the vehicles will use the blue area.

B Exemplar Tasks

B.1 Visual Navigation

In this task, the agent is initialized at a random location in the environment at the beginning of each episode, while the target object's location and category remain fixed throughout. The agent must rely on its first-person view observations and the relative spatial position of the target as input. The ultimate objective is to locate the target object within 2000 steps. Success is defined by the agent reducing the relative distance to less than 3 meters and aligning its orientation such that the relative rotation between the target and the agent is smaller than 30 degrees (in the front of the agent). This setup challenges the agent to optimize its movements and decision-making while adapting to the randomized starting conditions and dynamic environment. All methods in the task share the same discrete action space to control the movement, consisting of moving forward (+1 meter/s), moving backward (-1 meter/s), turning left (-15 degrees/s), turning right (+15 degrees/s), jumping (two continuous jumping actions trigger the climbing action), crouching, and holding position. This action space enables the agent to navigate and interact with complex 3D environments, making strategic decisions in real-time to reach the target object efficiently. The step reward for the agent is defined as:

$$r(t) = \tanh\left(\frac{dis2target(t-1) - dis2target(t)}{max(dis2target(t-1), 300)} - \frac{|Ori|}{90^\circ}\right) \tag{1}$$

where $dis2target(t)$ is the Euclidean distance between the agent and the target at a given timestep t and $|Ori|$ is the absolute orientation error (in degrees) between the agent's current heading and the direction toward the target, normalized by 90°

B.2 Active Visual Tracking

Referring to previous works (Zhong et al., 2024), we use human characters as an agent player and a continuous action space for agents. The action space contains two variables: the angular velocity and the linear velocity. Angular velocity varies between $-30^\circ/s$ and $30^\circ/s$, while linear velocity ranges from $-1\ m/s$ to $1\ m/s$. In the agent-centric coordinate system, the reward function is defined as:

$$r = 1 - \frac{|\rho - \rho^*|}{\rho_{max}} - \frac{|\theta - \theta^*|}{\theta_{max}} \tag{2}$$

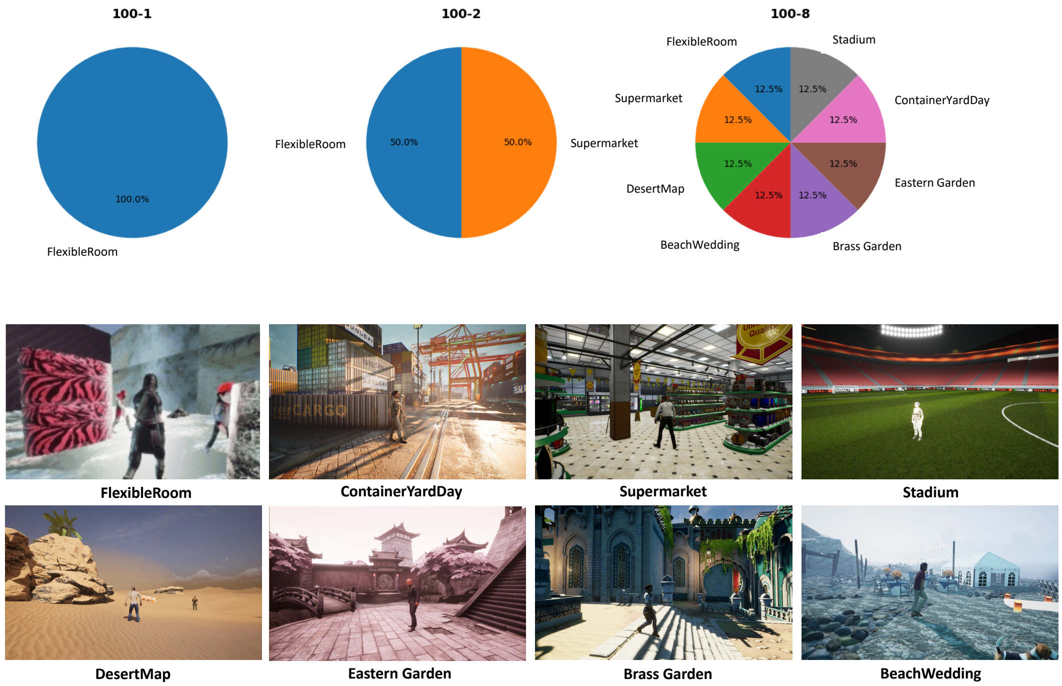

Figure 11: The 8 environments used for collecting offline dataset.

where (ρ, θ) denotes the current target position relative to the tracker, $(\rho^*, \theta^*) = (2.5m, 0)$ represents the expected target position, i.e., the target should be $2.5m$ in front of the tracker. The error is normalized by the field of the view $(\rho_{max}, \theta_{max})$. During execution, an episode ends with a maximum length of 500 steps, applying the appropriate termination conditions. In the experiment, we adopt the original neural network structure and parameters, as listed in Table 9 and 10.

B.3 Task Configuration In a JSON File

We provide an example of the task configuration JSON file in Figure 12. Using the JSON file, we can easily set the configuration of the binary, the continuous and discrete action space for each agent, the placement of the binding camera, choose the area to reset, and other hyper-parameters about the environments.

B.4 Collecting Demonstration for Active Visual Tracking

To demonstrate the flexibility of the environment, we use state-based expert policy and the multi-level perturbation strategy (Zhong et al., 2024) to automatically generate various imperfect demonstrations as the offline dataset. For active visual tracking, we employ three distinct datasets for training agents via offline reinforcement learning (Offline RL) algorithms, referred to as *1 Env.*, *2 Envs.*, and *8 Envs*. The detailed composition of each dataset is depicted in Figure 11. For the *1 Env.* dataset, we use only the FlexibleRoom, an abstract environment enriched with diverse augmentation factors, to gather 100k steps of trajectory data. For 2 Envs., we collect 50k step trajectories from FlexibleRoom and an additional 50k steps from the Supermarket environment. The 8 Envs. dataset involves eight different environments, with 12.5k steps collected from each. Therefore, **the total amount of data in the three datasets is the same (100k) to ensure the fairness of the comparison.** These dataset configurations aim to highlight the critical role of environment diversity in enhancing the generalization capabilities of embodied AI agents.

A Json File for Task Configuration

```
"env_name": env_name,
"env_bin":path-to-binary,
"env_map": map_name,
"env_bin_win": path-to-binary(for windows),
"third_cam": {"cam_id": 0,"pitch": -90,"yaw": 0,"roll": 0,"height_top_view":
    1460.0,"fov": 90},
"height": 460.0,
"interval": 1000,
"agents": {
    "player": {
        "name": ["BP_Character_923"],
        "cam_id": [3],
        "class_name": ["bp_character_C"],
        "internal_nav": true,
        "scale": [1,1,1],
        "relative_location": [20,0,0],
        "relative_rotation": [ 0,0,0],
        "head_action_continuous": {"high": [15,15,15], "low": [-15,-15,-15]},
        "head_action": [ [0,0,0],[0,30,0],[0,-30,0]],
        "animation_action": ["stand","jump","crouch"],
        "move_action": [
        [angular, velocity]
            ...
        ],
        "move_action_continuous": {"high": [30,100],"low": [-30,-100]}
    },
    "animal": {
        "name": ["BP_animal_2"],
        "cam_id": [1],
        "class_name": ["BP_animal_C"],
        "internal_nav": true,
        "scale": [1,1,1],
        "relative_location": [20,0,0],
        "relative_rotation": [0,0,0],
        "move_action": [
            [angular, velocity]
            ...
        ],
        "move_action_continuous": { "high": [30,100],"low": [-30,-100]}
    },
    "drone": {
        "name": ["BP_Drone01_2"],
        "cam_id": [2],
        "class_name": ["BP_drone01_C"],
        "internal_nav": false,
        "scale": [ 0.1,0.1,0.1],
        "relative_location": [0,0,0],
        "relative_rotation": [0,0,0],
        "move_action": [
          [angular, velocity]
            ...
        ],
        "move_action_continuous": {"high": [1,1,1,1],"low": [-1,-1,-1,-1]}
    }
},
"safe_start": [
    [x,y,z],
    ...
],
"reset_area": [x_min,x_maxin,y_min,y_max,z_min,z_max],
"random_init": false,
"env": {"interactive_door": []},
"obj_num": 466,
"size": 192555.0,
"area": 9900.0,
"bbox": [110.0, 90.0,19.45]
```

Figure 12: An example of the task configuration file in JSON format.

C Implementation Details of Agents

C.1 RL-based Agents

Learning to navigate with online reinforcement learning. For navigation, we construct an RL-based end-to-end model, using A3C (Mnih et al., 2016) to accelerate online reinforcement learning in a distributed manner. The model's structure is as follows: a mask encoder extracts spatial visual features from the segmentation mask, which are then passed to a temporal encoder to capture latent temporal information. Finally, the spatiotemporal features, concatenated with the target's relative spatial position, are fed into the actor-critic network to optimize the actor layer for action prediction. The detailed network structure and parameters used in the experiment are listed in Table 7 and 8. Here, we provide the training curves in *Roof* and *Factory* environments, depicted in Figure 16. In the *Factory*, we set the number of workers to 4, while in the *Roof*, the number of workers is set to 6. It can be observed that, for Online RL, the number of workers and the complexity of environments have a significant impact on training efficiency. Looking forward, we anticipate that offline-based algorithms can effectively address the challenges of training efficiency and generalization.

Table 7: Details the neural network structure of RL-based agent for navigation task, where 5×5-32S1 means 32 filters of size 5×5 and stride 1, FC256 indicates the fully connected layer with output dimension 256, and LSTM128 indicates that all the sizes in the LSTM unit are 128.

Module	Mask Encoder							
Layer#	CNN	Pool	CNN	Pool	CNN	Pool	CNN	Pool
Parameters	5×5-32$S1$	2-S2	5×5-32$S1$	2-S2	4×4-64$S1$	2-S2	3×3-64$S1$	2-S2
Module	Temporal Encoder		Actor			Critic		
Layer#	FC	LSTM	FC			FC		
Parameters	256	128	2			2		

Table 8: The experiment setting and hyper-parameters used for training the RL-based navigation agent.

Name	Value	Name	Value
Learning Rate	1e-4	LSTM update step	20
workers (Roof)	6	LSTM Input Dimension	256
workers (Factory)	4	LSTM Output Dimension	128
Position Input Dimension	2	LSTM Hidden Layer size	1

Learning to track with offline reinforcement learning. For the tracking task, we adopt an offline reinforcement learning (Offline RL) approach to enhance training efficiency and improve the agent's generalization to unknown environments. Specifically, we build an end-to-end model trained using offline data and the conservative Q-learning (CQL) strategy (Kumar et al., 2020). We adopt the same model structure from the latest visual tracking agent (Zhong et al., 2024), consisting of a Mask Encoder, a Temporal Encoder, and an Actor-Critic network. Detailed model structures and training parameters are summarized in Table 9 and 10. Additionally, we provide the model's loss curves under different dataset setups, as shown in Figure 15. The model achieves near-convergence within two hours across all dataset setups. To ensure the loss curves stabilize fully, we continued training for an additional three hours, during which no significant further decrease in the loss was observed. A comprehensive evaluation of the model's performance is presented in Tables 11 and 12, highlighting its strong generalization to unseen environments and robustness to dynamic disturbances. The training efficiency, generalization capability, and robustness achieved by offline RL further reinforce our belief that offline RL methods will become a mainstream approach for rapid prototyping and iteration in embodied intelligence systems.

Table 9: Network structure used in the offline RL method (Zhong et al., 2024), where 8×8-16S4 means 16 filters of size 8×8 and stride 4, FC256 indicates a fully connected layer with dimension 256, and LSTM64 indicates that all sizes in the LSTM unit are 64.

Module	Mask Encoder			Temporal Encoder	Actor	Critic
Layer#	CNN	CNN	FC	LSTM	FC	FC
Parameters	8×8-16S4	4×4-32S2	256	64	2	2

Table 10: The hyper-parameters used for offline training and the policy network.

Name	Value	Name	Value
Learning Rate	3e-5	LSTM update step	20
Discount Factor	0.99	LSTM Input Dimension	256
Batch Size	32	LSTM Output Dimension	64
LSTM Hidden Layer size	1		

C.2 VLM-BASED AGENTS

We built agents with a reasoning framework based on the Large Vision-Language Model. We employ OpenAI GPT-4o as the base model. System prompt used in the navigation task, as shown in Figure 14 and system prompt used in the tracking task, as shown in Figure 13.

C.3 HUMAN BENCHMARK FOR NAVIGATION

In the navigation task, we incorporated human evaluation as a baseline for comparison to demonstrate the existing gap between the current method and optimal navigation performance. Specifically, **five male and five female** evaluators participated in the assessment, performing the same navigation tasks under comparable conditions.

Before each human evaluator began their assessment, we provided a free-roaming perspective to familiarize them with the map structure and clearly conveyed the target's location and image. This ensured that human evaluators had a comprehensive understanding of the environment and the target's position. During the evaluation, the player was randomly initialized in the environment, and human evaluators used the keyboard to control the agent's movements. Each human evaluator repeated the experiment five times, providing multiple data points to ensure reliability and reduce variability in performance measurements. The termination conditions for the evaluation were identical to those applied to the RL-based agent, ensuring consistency in the comparison.

System Prompt used for active tracking

```
Objective:
You are an intelligent tracking agent designed to control the robot to track the person
      in the view. The first person in your view is your target. You need to provide
     concrete moving strategie to helo robot tracking the target in the given
     environment.

Representation details:
1. Moving instructions are concrete actions that the robot can take to adjust its
     viewpoint and distance to the target. The moving instructions include:
    -move closer: Move the robot closer to the target. This should be chosen when the
         target is too far away from the robot and there is no obstacle in the way.
    -move further: Move the robot further away from the target. This should be 2chosen
         when the target is too close to the robot and only part of the target body is
         visible in the view.
    -keep current: Maintain the current distance and angle between the robot and the
         target. This is chosen when the target is fully observable in the view and
         there is enough space in front of both tracker and target without any
         potential obstacles may cause collision and occlusion.
    -turn left:  Turn the robot to left direction, the target will move towards the
         right side in next frame.
    -turn right: Turn the robot to right direction, the target will move towards the
         left side in next frame.
Input Understanding:
1.**Image:** We provide a first-person view observation of the robot to help you
     understand the surrounding environment. The observation is represented as a color
     image from the tracker's first-person perspective.

Output Understanding:
1. **Moving Strategy:** A temporal reasonable move strategy to adjust the robot
     viewpoint and distance to achieve robots's long-term tracking task. This should be
      represented as a concrete moving instructions, the instructions should be choose
     from "move closer", "move further" ,"keep current", "turn left","turn right".
     Format - [Keep current].

Strategy Considerations:
1.If the person's horizontal position in the robot's field of view deviates from the
     center by more than 25% of the image width, we consider the target to be on one
     side of the image, otherwise we say the target is near the center.
2.To provide a reasonable moving strategy, you should think step by step based on the
     input image and the following hints:
    1)If the person is too close to the robot and the target in the image is clipped,
         robot should move further first to obtain a better view.
    2)If the person's size in the view is too small in the image, robot should move
         closer to obtain a better view.
    3)If the person may occluded by obstacles or structures in the future, the robot
         should move closer to avoid losing the person in the next frame.
    4)If the person is near the right edge in the image and there is no immediate
         obstacle in front of robot, the robot should turn right to keep person near
         center in the image.
    5)If there is immediate hinder obstacles in front of the robot, turn right or left
         to a clean space first.
    6)If there is any potential occlusion effect or obstacles on either side of the
         person's walking path, the robot should move closer to avoid losing the person
          in the next frame.
    7)If there is no person in the current image, turn right or turn left to search the
          person.
Instructions:
1.Provide ONLY the decision in the [output:] strictly following the format without
     additional explanations or additional text.
```

Figure 13: System prompt used for tracking.

System Prompt used for navigation

```
Objective:
You are an intelligent navigation agent designed to control the robot to navigate to
     the target object location based on first-person observation and provide a
     relative position between the robot and the target. You need to provide an action
     sequence to help the robot move to the target location.

Representation details:
1. Relative Position: This contains three elements, in the format - [Distance,
     Direction, Height].
    -Distance: The relative distance between the robot and the target object.
    -Direction: The target object's relative direction to the robot, represented in
        degrees. \
           A positive value represtent the target is on the right side of the robot
                with corresponding angle and a negative value represent the target is
                on the left side of the robot with corresponding angle. \
           The absolute value of the angle larger than 90 degree means the target is
                behind the robot. \
    -Height: The relative vertical position, where a positive value indicates that the
        target is higher than the robot.
1. Actions: These are the movements the robot can perform to adjust its position. The
     available actions include:
    -Move Forward: Propel the robot forward by 100 centimeter.
    -Move Backward: Propel the robot backward by 100 centimeter.
    -Turn Left: Rotate the robot 15 degrees to the left.
    -Turn Right: Rotate the robot 15 degrees to the right.
    -Jump: Make the robot leap into the air, robot should use this action to jump over
        obstacles or climb over stairs.
    -Crouch: Lower the robot into a crouching position for 2 seconds, after which it
        will automatically stand up.
    -Keep Current: Maintain the robot's current position without any movement.

Input Understanding:
1.**Image:** We provide a first-person view observation of the robot to help you
     understand the surrounding environment. The observation is represented as a color
     image from the robot's first-person perspective.
2.**Relative Position:** This data provides the target object's relative position to
     the robot, including the distance, direction, and height. The distance is measured
      in centimeters, the direction in degrees, and the height in centimeters.
Output Understanding:
1. **Action Sequence:** This is a series of Three continuous actions that the robot
     should take to navigate toward the target object. Each sequence must consider the
     provided relative position data and the first-person observation. \
                        The actions should be ordered logically to effectively move the
                              robot closer to the target, adjusting its direction,
                             distance, and height as needed. \
                        The action sequence should be clear and executable, enabling
                             the robot to reach the target efficiently while avoiding
                             obstacles and maintaining stability
                        in the format - [Action1, Action2, Action3]. Each action should
                              be choose from the available actions mentioned above.

Strategy Considerations:
1.Assessing Relative Position: Begin by evaluating the target object's relative
     position in terms of distance, direction, and height to inform the action sequence
     .
2.Action Combination for Navigation: Utilize the action sequence to create effective
     combinations, each action will last for 1 seconds. For example:
        -Consider using multiple consecutive actions like [Move Forward, Jump, Jump] to
              climb over the front obstacles or boxes.
        -Consider using [Move Backward,Move Backward,Move Backward] to move the robot
             avoid a front wall or fence.
3.Obstacle Detection: Leverage the first-person observation to identify obstacles.
     Based on their location, formulate action sequences that facilitate smooth
     navigation while avoiding collisions.
4.Efficient Pathing: Ensure the action sequence is designed to dynamically adjust the
     robot movement forward target object, which is minimize the distance and direction
      value in **Relative Position**.
5.Sequence Validation: Validate the generated action sequence and consider past
     memories to ensure it is practical given the current environment and obstacles,
     making long-term adjustments as necessary.
Instructions:
1.Provide ONLY the action sequence in the [output:] strictly following the format -[
     Action1, Action2, Action3], without additional explanations or additional text.
```

Figure 14: System prompt used for navigation.

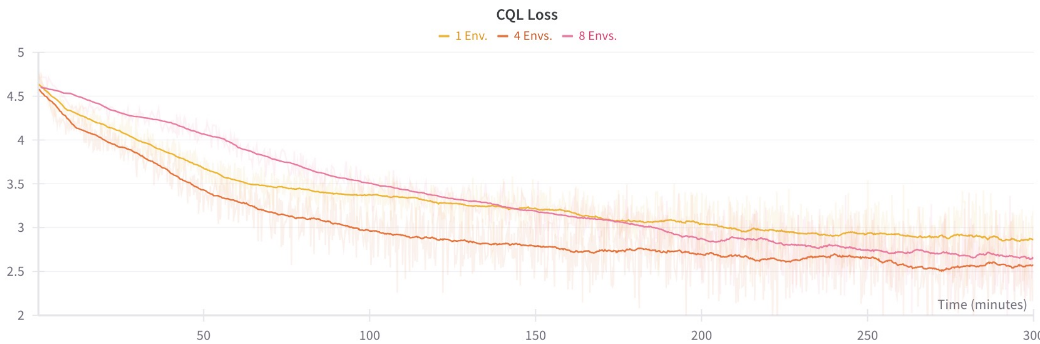

Figure 15: The CQL loss curve during offline training with different offline datasets.

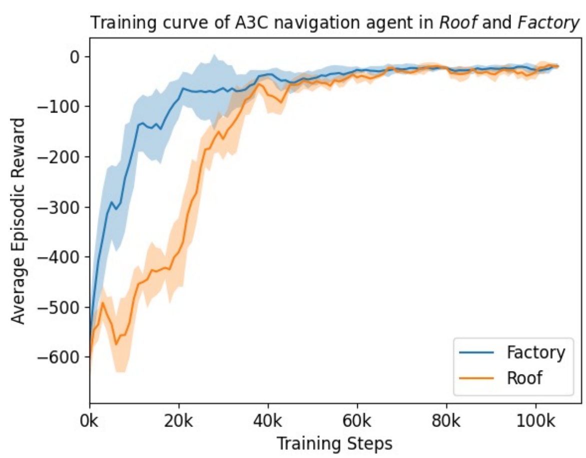

Figure 16: The learning curves for RL-based navigation agent in two environments: Roof and Factory. We use A3C (Mnih et al., 2016) to learn the navigation policy via trial-and-error interactions. In the Factory (blue line plot), the number of asynchronous workers is set to 4, while in the Roof environment (orange line plot), the number of asynchronous workers is set to 6.

D Additional Results

D.1 Learning Curve

We provide the CQL loss curve under the *1 Env., 4 Envs. and 8 Envs.* training setup. As shown in Figure 15, the offline model approaches convergence after two hours and we continued training for another three hours after nearing convergence, observing no significant further decrease in the loss. Note that the offline training was conducted on a Nvidia RTX 4090 GPU.

D.2 Evaluate Tracking Agents across 16 Unseen Environments

We provide the detailed quantitative evaluation results (episodic returns, episode length, success rate) of the RL-based embodied tracking agents across 16 environments, listed in Table 11. In each environment, we report the average results over 50 episodes. The results show that in the *Palace Maze*, which contains abundant structural obstacles, the agent's tracking performance was generally weaker compared to the other three categories. In contrast, the agent performed generally better in *Lifelike Urbanity*, characterized by its relatively regular and flat terrain. Additionally, we observed that as the diversity of the training environments increased, the agent's tracking performance improved across all four environment categories. This highlights the positive impact of diverse training data on enhancing the agent's overall tracking effectiveness. We also provide vivid demo videos in `https://unrealzoo.notion.site/task-evt`.

Table 11: Quantitative evaluation results of the offline RL method across 16 environments. The environments are grouped into four categories: Compact Interior, Wildscape Realm, Palace Maze, and Lifelike Urbanity. The table compares the performance of agents trained on different offline dataset settings: 1 Env. (single environment), 2 Envs. (two environments), and 8 Envs. (eight environments). Each cell presents three metrics from left to right: Average Episodic Return (ER), Average Episode Length (EL), and Success Rate (SR).

Category	Environment Name	1 Env. ER/EL/SR	2 Envs. ER/EL/SR	8 Envs. ER/EL/SR
Compact Interior	Bunker	241/412/0.56	245/391/0.56	234/429/0.70
	StorageHouse	213 /424 /0.68	275/449/0.76	170/434/0.64
	SoulCave	229/402/0.60	252/422/0.56	206/405/0.58
	UndergroundParking	179/391/0.56	250/424/0.62	184/410/0.60
Wildscape Realm	Desert Ruins	209/392/0.54	293/449/0.70	277/453/0.70
	GreekIsland	245/411/0.62	264/423/0.64	257/466/0.78
	SnowMap	204/399/0.62	322/456/0.78	278/474/0.86
	RealLandscape	171 /383/0.42	225/372/0.44	223/444/0.70
Palace Maze	WesternGarden	230/403/0.54	209/408/0.54	296/472/0.82
	TerrainDemo	232/411/0.56	233/403/0.56	192/411/0.56
	ModularGothicNight	190/360/0.52	244/423/0.62	272/456/0.76
	ModularSciFiSeason1	168/365/0.42	172/354/0.42	211/393/0.48
Lifelike Urbanity	SuburbNeighborhoodDay	224/422/0.64	328/457/0.72	242/457/0.76
	DowntownWest	296/460/0.78	317/456/0.76	292/469/0.86
	Factory	278/434/0.64	291/452/0.74	249/435/0.64
	Venice	295/441/0.70	323/448/0.82	294/474/0.84

Table 12: Quantitative evaluation results of the tracking agents across 4 different category environments with **4 distractors (4D), 8 distractors (8D), and 10 distractors (10D)** respectively. The table compares the performance of agents trained on different offline dataset settings: 1 Env. (single environment), 2 Envs. (two environments), and 8 Envs. (eight environments). Each cell presents three metrics from left to right: Average Episodic Return (ER), Average Episode Length (EL), and Success Rate (SR).

Category	Environment Name	1 Env. ER/EL/SR	2 Envs. ER/EL/SR	8 Envs. ER/EL/SR
Compact Interior	StorageHouse (4D)	117/343/0.40	181/375/0.52	190/428/0.62
	StorageHouse (8D)	143/341/0.34	151/338/0.44	165/366/0.49
	StorageHouse (10D)	81/324/0.36	109/331/0.42	107/357/0.50
Wildscape Realm	DesertRuins (4D)	317/469/0.72	333/456/0.70	354/466/0.74
	DesertRuins (8D)	213/406/0.50	316/445/0.58	267/444/0.68
	DesertRuins (10D)	188/390/0.44	252/382/0.50	253/447/0.64
Palace Maze	TerrainDemo (4D)	221/398/0.44	286/454/0.65	312/460/0.77
	TerrainDemo (8D)	211/384/0.39	239/412/0.49	252/420/0.52
	TerrainDemo (10D)	189/377/0.36	232/404/0.48	224/429/0.66
Lifelike Urbanity	SuburbNeighborhoodDay (4D)	192/407/0.46	256/381/0.50	265/392/0.60
	SuburbNeighborhoodDay (8D)	131/325/0.36	229/369/0.48	247/385/0.56
	SuburbNeighborhoodDay (10D)	162/355/0.44	180/340/0.40	165/376/0.44

D.3 Evaluate Tracking Agents across Unseen Social Environments

We select 4 environments from different categories as the testing environments, including StorageHouse, DesertRuins, TerrainDemo, and SurburNeighborhoodDay. We test the distraction robustness of the social tracking agents by adding different numbers of distractors (4, 8, 10) in the environment. The distractors randomly walk around the environment, which may produce various unexpected perturbations to the tracker, such as visual distractions, occlusion, or blocking the tracker's path. As shown in Table 12, the tracking performance of the three agents steadily decays with the increasing number of distractors.