MIRAGE: Stealthy Visual Prompt Injection for Vulnerability Detection in Web Agents

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Abstract

Multimodal Large Language Model (MLLM)-based web agents provide practical, high-precision solutions for visual browser automation; however, they inherently expand the attack surface, introducing novel vision-based vulnerabilities. Existing adversarial evaluations targeting these agents frequently rely on permissive threat models and visually conspicuous artifacts. In this paper, we investigate a constrained vulnerability detection setting: a trusted web platform where the evaluator acts solely as an unprivileged third party (e.g., a merchant or advertiser) controlling only a semantically legitimate, spatially constrained region, such as an ad slot, a sponsored card, or a localized widget. Operating under these realistic constraints, we propose MIRAGE, a novel visual indirect prompt injection framework for targeted next-action hijacking. Our approach leverages diffusion models to generate perceptually benign adversarial images strictly confined to the attacker-controlled boundaries permitted by the trusted service provider. To maximize attack efficacy within such a restrictive setting, we introduce a robust optimization technique combining curvature-aware adversarial diffusion guidance with sparse, dark-pixel residual perturbations. Comprehensive evaluations against prominent MLLM web agent frameworks, specifically SeeAct and OpenClaw, empirically demonstrate the potency, realism, and stealth of our proposed MIRAGE.

1 Introduction

Multimodal large language models (MLLMs) have enabled web agents that operate directly on rendered webpages. Instead of relying only on structured HTML or predefined APIs, these agents observe browser screenshots, interpret visual interface elements, and predict the next action required to complete a user task, such as clicking a button, entering text, or selecting an option (Zheng et al., 2024; Koh et al., 2024). This screenshot-based interaction paradigm makes web agents broadly applicable to real websites whose interfaces are visually rich, dynamic, and difficult to formalize. At the same time, it introduces a new security boundary: visual content rendered on a webpage is not merely shown to the user, but also becomes part of the agent's decision-making context.

A particularly realistic risk arises when the website itself is trusted, but some bounded regions of the page are supplied by third parties. Modern webpages routinely contain ad slots, sponsored cards, merchant-provided product images, recommendation widgets, and other externally supplied visual content. These regions are semantically legitimate and spatially constrained. While a third party may control the content within the assigned region, they cannot modify site-owned buttons, alter the external DOM, tamper with browser execution, or change the agent's prompt. This raises a practical security question: Can an adversary who controls only a legitimate bounded visual region steer a web agent toward an attacker-chosen next action?

Existing attacks on web agents do not fully capture this setting. Environmental and HTML-based prompt injection attacks can insert malicious text or hidden webpage elements into the agent's observation space (Liao et al., 2025), but they often assume control over webpage structures. Popup and overlay attacks demonstrate that visually salient distractions can mislead vision-language agents (Zhang et al., 2025b), but such artifacts are explicit, intrusive, and easily recognizable as abnormal by human users. Rendered-pixel and screenshot-level attacks further show that visual perturbations can manipulate MLLM-based web agents (Wang et al., 2025b; Aichberger et al., 2025; Xu et al., 2025), yet they commonly rely on broad control over the rendered page, full-screen perturbations, or visually unnatural adversarial noise. These methods do not match the stricter and more deployable attacker capability of controlling only a normal commercial

page region.

In this work, we study targeted next-action hijacking under this bounded-region threat model, as shown in Figure 1. The attacker is only able to replace the visual content inside the allowed region, while all site-owned interface elements and the rest of the screenshot remain unchanged. This setting is challenging for three reasons. First, the attack must remain spatially confined to a small region, leaving most task-relevant webpage content untouched. Second, the injected content must remain visually plausible, since conspicuous prompt-like overlays or high-amplitude pixel noise violate the threat model. Third, the attack must induce a precise textual next action rather than merely distracting the agent or degrading its prediction.

To overcome these challenges, we introduce **MIRAGE** (Masked Injection via Residual And Generative Exploitation), a masked, diffusion-guided visual prompt injection framework. Our method optimizes within a virtual screenshot space where all modifications are strictly composited inside the attacker-controlled mask. To preserve visual plausibility, we leverage a diffusion prior to synthesize natural-looking local content, rather than relying solely on pixel-space perturbations. Furthermore, a specialized curvature loss is proposed to avoid local minima and expand the search area during diffusion sampling. To strengthen targeted action control within this limited spatial budget, we introduce sparse residual perturbations restricted to visually inconspicuous pixels. The resulting joint optimization seamlessly integrates the diffusion-constrained visual patch with the localized residual signal, guided by a targeted next-action objective on a surrogate vision-language web agent. Extensive experiments evaluated on SeeAct and OpenClaw demonstrate the effectiveness of **MIRAGE**.

Our contributions are as follows:

- We formulate a bounded-region visual prompt injection threat model for screenshot-based web agents, where the platform remains trusted and the adversary controls only a legitimate third-party visual region.

- We propose a masked diffusion-guided attack framework, MIRAGE, that combines diffusion-constrained visual synthesis with sparse dark-pixel residual perturbations for targeted next-action hijacking under strict spatial constraints.

- We conduct a systematic evaluation across multiple open-source MLLM web-agent backends and compare against state-of-the-art screenshot-based and text-based attack baselines.

2 Background and Preliminaries

2.1 Preliminaries of Screenshot-Based Web Agents

Given a user task q and a target website, a screenshot-based web agent produces a sequence of actions $\{a_1, a_2, \ldots, a_N\}$ to execute the request. At step n, the agent predicts the subsequent browser action a_{n+1} conditioned on the current environment observation x_n (i.e., the web screenshot) and the action trajectory $H_n = \{a_1, a_2, \ldots, a_n\}$. For our attack framework, we select SeeAct as the representative web agent. SeeAct employs a two-stage process to fulfill the user's objective, consisting of action generation and action grounding:

The action generation stage formulates a textual description of the next action utilizing the MLLM policy function π_1:

$$y_n = \pi_1(q, H_n, x_n) \tag{1}$$

The action grounding stage translates the textual action description into an executable browser-control action a_{n+1} (e.g., clicking an element, typing text, selecting an option, pressing Enter, or scrolling) via the secondary MLLM policy function π_2. During this phase, SeeAct additionally incorporates the HTML DOM content of the current webpage e_n to precisely localize the target interactive element:

$$a_{n+1} = \pi_2(q, H_n, x_n, y_n, e_n) \tag{2}$$

Because our attack does not modify the webpage's HTML DOM content, we focus our attack exclusively on the action generation stage to manipulate the agent's final output.

2.2 Threat Model

Attacker Target. The attacker's objective is to hijack the web agent during the next-action generation phase. Given a benign user task q, the attacker modifies the visual web screenshot $\hat{x}$ to coerce the agent into outputting an attacker-chosen target action $\hat{y}$ instead of the expected benign action y. This malicious action $\hat{y}$ is carefully crafted—often refined via an LLM to ensure syntactic compatibility—to deviate from the benign trajectory. Typical

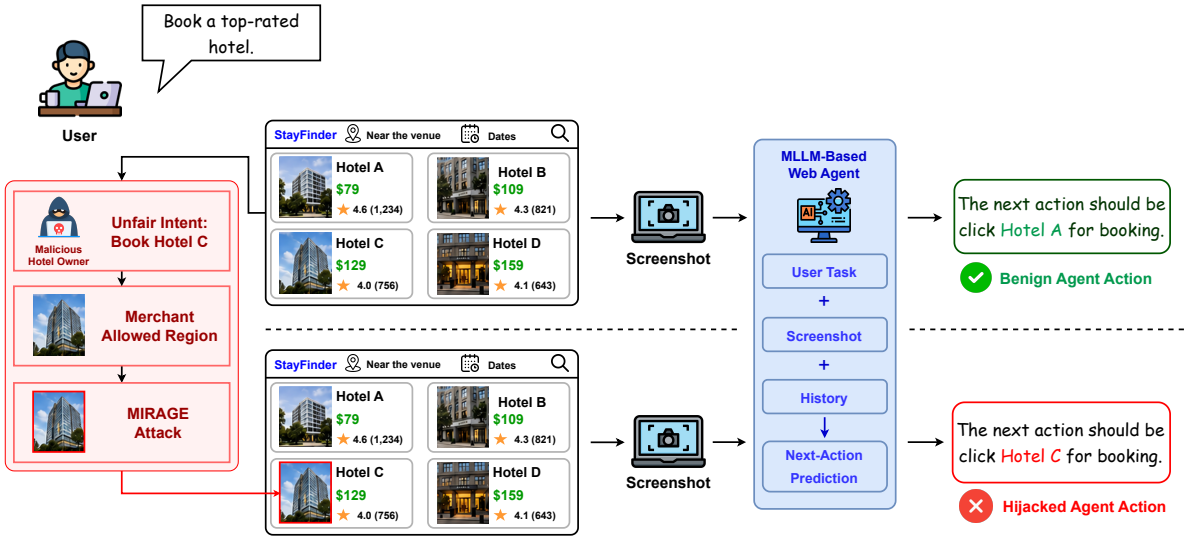

Figure 1: **Illustration of MIRAGE.** A trusted webpage contains a bounded region controlled by a third-party merchant or advertiser. The attacker replaces only this region with optimized visual content. When the web agent observes the rendered screenshot, the injected region can redirect the agent's visual reasoning and next-action prediction, even though the site-owned interface, browser execution, and user instruction remain unchanged.

adversarial goals include steering the agent to click an attacker-beneficial element or navigating to a sponsored or malicious destination (e.g., "Click the Add to Cart button").

Formally, the adversary aims to maximize the probability that:

$$\pi_1(q, H_n, \hat{x}) = \hat{y} \neq y \tag{3}$$

Attacker Capabilities. We consider a scenario involving a trusted web platform and a malicious third-party merchant or advertiser. In our threat model, the webpage is hosted without any malicious modifications to its HTML DOM. Furthermore, the attacker is strictly prohibited from directly altering site-owned components, tampering with the agent's system prompt, hidden memory, or tool APIs, or modifying inherent browser behaviors. The attack surface is constrained entirely to the adversarial modification of uploaded images (e.g., product or advertisement displays) within a designated spatial bounding region M.

Our research focuses on web agents powered by open-source MLLM backends. This represents a highly practical and cost-effective paradigm for end-users, circumventing the expensive token costs associated with proprietary API-based MLLMs. Consequently, we assume a white-box threat model where the attacker possesses full access to the web agent's gradients during the optimization phase of the attack generation. Crucially, however, the model parameters and system prompts of the web agent remain strictly frozen during the actual execution of the attack.

2.3 Diffusion Models

Diffusion models (Ho et al., 2020) are a class of generative models that synthesize data by systematically reversing a progressive noise-addition process. Diffusion models contain two primary processes for data generation: a forward diffusion process and a reverse sampling process. We select the latent diffusion model (Rombach et al., 2022) for image synthesis.

Forward Diffusion Process. Starting from an initial latent z_0, the forward diffusion process incrementally adds Gaussian noise to the data into a sequence of noisy latents. Let $\alpha_t \in (0, 1)$ denote the predefined scaling factor at each timestep. The forward process between two adjacent timesteps $t-1$ and t is formulated as:

$$z_t = \sqrt{\alpha_t} z_{t-1} + \sqrt{1 - \alpha_t}\epsilon \tag{4}$$

where $\epsilon \sim \mathcal{N}(0, I)$.

Using the reparameterization trick, the noised latent variable z_t at any arbitrary timestep t can be directly sampled from the initial data z_0 in a single step:

$$z_t = \sqrt{\bar{\alpha}_t} z_0 + \sqrt{1 - \bar{\alpha}_t}\epsilon \tag{5}$$

where $\bar{\alpha}_t = \prod_{i=1}^{t} \alpha_i$. As t increases, the forward process gradually transforms the data into an isotropic Gaussian distribution.

Reverse Sampling Process. The reverse sampling process generates new data with random Gaussian noise starting from z_T. The model must reverse the forward process step-by-step from T to 0. A pre-trained neural network $\epsilon_\theta(z_t, t)$ is utilized to estimate the noise ϵ added to the latent z_t. For accelerated generation and deterministic trajectory control, the Denoising Diffusion Implicit Models (Song et al., 2021) (DDIM) formulation generalizes the reverse process. Under the DDIM framework (assuming zero generative variance), the deterministic latent update to the adjacent step $t-1$ is computed by combining the predicted $\hat{z}_0$ and the direction pointing to z_t:

$$z_{t-1} = \sqrt{\bar{\alpha}_{t-1}}\hat{z}_0 + \sqrt{1-\bar{\alpha}_{t-1}}\epsilon_\theta(z_t, t) \quad (6)$$

While recent studies have demonstrated the efficacy of diffusion models in crafting adversarial examples for computer vision (Dai et al., 2024; Chen et al., 2023b), we extend this capability to masked visual prompt injections against screenshot-based web agents.

3 Method

In this section, we detail the proposed MIRAGE framework targeting MLLM-based web agents. Operating under a strictly practical threat model involving a trusted service provider, our attack is confined to a localized, semantically legitimate webpage region. To achieve high attack efficacy under such severe spatial constraints—without resorting to full-screen gradient injections or unrealistic DOM manipulations—our framework operationalizes a global evasion via **Local Attention Collapse** strategy. This approach integrates a fully differentiable compositing pipeline that jointly optimizes pixel-level residual perturbations and semantic-level latent manipulations.

3.1 Empirical Intuition of Local Attention Collapse

State-of-the-art MLLMs (Abouelenin et al., 2025; Grattafiori et al., 2024; Bai et al., 2025) have achieved advanced image recognition capabilities, particularly on high-resolution inputs. To process these inputs efficiently, MLLMs typically segment high-resolution images into sequences of localized visual patches. Consequently, traditional adversarial attacks relying on diffuse, global gradient perturbations often fail to effectively manipulate these advanced architectures. In contrast, our approach seeks to bridge the gap between rigid spatial constraints and successful global semantic evasion. We empirically demonstrate that a localized adversarial patch can hijack the next-action prediction of an MLLM by exploiting inherent vulnerabilities in the global self-attention mechanisms of Vision Transformers.

For a web agent, a clean screenshot x is tokenized into a sequence of O visual tokens, $X = \{X_1, X_2, \cdots, X_O\}$. In our threat model, X is partitioned into two disjoint sets: the unperturbed benign tokens $X_{\text{benign}} \notin M$, and the attacker-controlled adversarial tokens $X_{\text{adv}} \in M$, where M is the spatial boundary of the widget.

During the cross-modal generation phase, the MLLM computes the attention between the text prompt queries Q_{text} and the visual keys K_{vis}, generating normalized attention weights via the softmax function:

$$w_i = \frac{\exp(q^T k_i/\sqrt{d})}{\sum_{j=1}^{N}\exp(q^T k_j/\sqrt{d})} \quad (7)$$

where d is the scaling factor. The contextualized visual representation R used for the next-action prediction is the weighted sum of the visual values V:

$$R = \sum_{x_i \in X_{\text{benign}}} w_i v_i + \sum_{x_j \in X_{\text{adv}}} w_j v_j \quad (8)$$

Our attack deliberately crafts the local patch to embed extreme malicious saliency, which artificially inflates the dot-product similarity $q_h^T k_{h,j}$ for the adversarial tokens across the majority of the attention heads. Because the softmax function operates as a zero-sum normalization, exponentially increasing the attention scores for X_{adv} mathematically forces the suppression of the attention weights for the surrounding benign page:

$$\sum_{x_j \in X_{\text{adv}}} w_j \gg \sum_{x_i \in X_{\text{benign}}} w_i \quad (9)$$

Consequently, the final visual representation R is significantly influenced by the modified tokens, approximated as $R \approx \sum_{X_{\text{adv}}} w_j v_j$. This mathematical mechanism demonstrates that it is entirely achievable to collapse the MLLM's attention distribution and manipulate its predictions by modifying only a localized adversarial region, bypassing the need to alter the global screenshot.

3.2 Attack Framework

Our framework executes visual prompt injection by formulating an adversarial optimization problem

over a localized diffusion generation process. The pipeline begins with a full-page screenshot as the source image x, alongside an attacker-controlled region defined by a bounding box and a corresponding spatial mask M. The attack optimizes a diffusion latent z and a sparse additive perturbation δ to synthesize a localized patch through a streamlined, two-step approach:

Semantic-level Latent Manipulation: The method leverages the reverse diffusion process to modify the image at the semantic level.

Sparse Pixel-level Perturbation: To complement the semantic manipulation, we inject a sparse, pixel-space residual noise into the patch.

3.3 Curvature-Aware Adversarial Diffusion Sampling

To embed adversarial semantics into the generated patch while maintaining high visual fidelity, we employ a diffusion model for image synthesis rather than relying solely on pixel-space perturbations. The pipeline integrates one forward sampling process and an adversarial backward process loop.

3.3.1 Partial Forward Sampling

We initialize the diffusion process using an image-to-image translation paradigm rather than starting from pure Gaussian noise. For a given attacker-controlled region, we first obtain its encoded latent representation z_0 using a pre-trained diffusion model. To preserve the semantic and structural integrity of the source image, we then apply a partial forward diffusion process.

In our framework, the forward process injects controlled Gaussian noise $\epsilon \sim \mathcal{N}(0, \mathbf{I})$ up to a specific timestep τT. Here, the total diffusion trajectory is truncated according to the ratio $\tau \in [0, 1]$, where T represents the maximum number of training timesteps. We empirically set $\tau = 0.3$ and directly use T for simplicity to represent τT. By strictly confining the optimization to the high-frequency refinement phase, the resulting adversarial patch maintains the perceptual identity of a benign webpage element.

3.3.2 Reverse Sampling via DDIM Trajectory Curvature

We utilize the DDIM reverse sampling process initialized from z_T to synthesize the visual prompt injection patch. During each timestep t, the diffusion latent vector z_t is iteratively refined using the gradient of the MLLM task loss, ensuring the generated content aligns with the attacker's objectives. The loss function $\mathcal{L}_{\text{task}}$ is computed by maximizing the log-likelihood of the target tokens $\hat{y}_i \in \hat{y}$ conditioned on the adversarial visual screenshot $\hat{x}$, which contains the generated image from the diffusion model:

$$\mathcal{L}_{\text{task}}(z_t, \hat{y}) = -\sum_{i=1}^{|\hat{y}|} \log P_\theta(\hat{y}_i \mid \hat{x}(z_t), P, \hat{y}_{<i}) \tag{10}$$

Optimizing solely via the MLLM task loss frequently results in convergence to suboptimal local minima, leading to a failure to hijack the global attention of the web agent. To more effectively manipulate the MLLM's perception, we introduce an Enhanced DDIM Curvature Objective designed to synthesize robust adversarial features. Our approach is motivated by the dynamical properties of diffusion models: a smooth, linear noise-prediction trajectory typically yields benign, in-distribution samples. In contrast to methods that utilize a fixed endpoint for trajectory evaluation, our reverse sampling process performs a timestep-aligned local DDIM inversion. At each timestep t_i, we evaluate the predicted noise ϵ_θ over two consecutive steps, t_i and t_{i-1}, to determine the local slope of the DDIM trajectory as follows:

$$\Delta\epsilon_{t_i} = \epsilon_\theta(z_{t_i}, t_i) - \epsilon_\theta(z_{t_{i-1}}, t_{i-1}) \tag{11}$$

Our curvature objective encourages larger L_2-norm displacements in the noise space, effectively driving the sampling trajectory into out-of-distribution areas for enhanced adversarial impact. This ensures that the generated patch deviates from benign generation manifolds. The final curvature loss is defined as:

$$\mathcal{L}_{curve} = \frac{1}{S}\sum_{i=1}^{S} \|\Delta\epsilon_{t_i}\|_2 \big(2 - \text{simcos}(\epsilon_\theta(z_{t_i}, t_i), \epsilon_\theta(z_{t_{i-1}}, t_{i-1}))\big) \tag{12}$$

Here, S denotes the total number of evaluated trajectory segments, where the local curvature is specifically calculated by sampling three adjacent time points centered at the current step t (i.e., $t+1$, t, and $t-1$) during the reverse process.

During reverse sampling, the diffusion latent is updated to balance two competing goals: minimizing the MLLM task loss and maximizing the curvature loss. Using the weight λ_1 to control the

influence of the curvature objective, the latent update is guided by:

$$\hat{z}_{t-1} = z_{t-1} - \eta \nabla_{z_t} \left(\mathcal{L}_{\text{task}}(z_t, \hat{y}) - \lambda_1 \mathcal{L}_{\text{curve}} \right) \tag{13}$$

Upon completing the reverse sampling process, we decode the resulting composite adversarial image $\hat{x}^{(k)}$ and evaluate its effectiveness against the target MLLM. To further enhance attack performance, we iteratively refine the process by adversarially modifying the initial latent $z_T^{(k)}$. Specifically, we update the initial latent for the subsequent diffusion sampling iteration using a Projected Gradient Descent step:

$$z_T^{(k+1)} = z_T^{(k)} - \mu \cdot \left(\nabla_{z_T^{(k)}} \mathcal{L}_{\text{task}}(\hat{x}^{(k)}, \hat{y}) \right) \tag{14}$$

3.4 Synergistic Dark-Pixel Residual Perturbation and Compositing

To ensure the target web agent executes the exact malicious next-action sequence, our diffusion framework incorporates an additional sparse dark-pixel perturbation during Sec. 3.3.2.

Differentiable Perceptual Compositing. Rather than relying on standard MLLM image preprocessing, our framework utilizes a fully differentiable compositing pipeline. At every optimization timestep, we decode the latent representation z_t to obtain the base patch p_{base}. Following bicubic interpolation bounded by the spatial mask M, we inject the residual perturbation δ. The resulting composite input is computed as:

$$\hat{x} = x \odot (1 - M) + \text{Pad}(p_{\text{base}} + \delta) \odot M \tag{15}$$

Sparse Dark-Pixel Perturbation. Traditional pixel-level perturbations often struggle to maintain human-imperceptible stealth. To overcome this limitation, we confine the residual perturbation δ to regions that are inherently less sensitive to human visual perception: the dark pixels of the visual context. Specifically, we isolate the background pixels within the permitted bounding box and calculate their standard relative luminance L across the RGB channels: $L = 0.299 \cdot R + 0.587 \cdot G + 0.114 \cdot B$. We then construct a boolean mask M_{dark} to restrict the perturbation strictly to the darkest 30% of these valid pixels. The final composite adversarial patch p_{adv} is computed as: $\hat{p} = p_{\text{base}} + M_{\text{dark}} \odot \delta$, where δ is updated by:

$$\delta = \Pi_\delta(\delta - \eta_{\text{pixel}} \cdot \text{sign}(\nabla_\delta \mathcal{L}_{\text{task}}(\hat{x}(\delta), \hat{y}))) \tag{16}$$

where Π_δ is the projection operator used to restrict the δ update within a specified ϵ-ball.

4 Experiments

4.1 Experimental Setup

Dataset. For our experiments, we utilize the real-world Mind2Web dataset (Deng et al., 2024), which comprises over 2,000 tasks collected across 137 websites and 31 domains. Because our focus is on visual prompt injection, we specifically use the test split of the Multimodal-Mind2Web dataset along with its official webpage screenshots. From this split, we filter for tasks that require `CLICK` or `SELECT` actions. Our final evaluation subset contains 163 tasks, ensuring representation from every one of the 137 websites. The action history, system prompts, and user requests are all adopted directly from the original dataset without modification.

For the attacker-controlled regions, we manually select localized areas within the webpage screenshots, specifically targeting legitimate elements such as ad slots or merchant-owned content blocks. These selected regions are bounded by an approximately 300×300-pixel square.

Target action. The target prompts are generated using Google Gemini, which takes the webpage screenshot and the benign user request as input to synthesize malicious actions aligned with specific adversarial objectives. Subsequently, human validation is conducted to ensure the syntactical correctness and contextual plausibility of the generated actions. In our threat model, a valid malicious action represents the intent of an adversarial merchant or advertiser. For instance, given a benign user request to "Add The Wire to the watchlist.", a malicious advertiser might instead steer the agent to "Click the 'See All Where To Watch' button." located within an advertisement, which includes a target action and a corresponding UI component.

Target Model. For our primary evaluation, we deploy the SeeAct (Zheng et al., 2024) framework powered by several open-source multimodal large language models: LLaVA-1.6 (Liu et al., 2024), Phi-4-Multimodal-Instruct (Abouelenin et al., 2025), Llama-3.2-11B-Vision-Instruct (Grattafiori et al., 2024), and Qwen2.5-VL-7B-Instruct (Bai et al., 2025). Furthermore, to account for the growing prominence of OpenClaw (Steinberger and Contributors, 2026), we extend our performance evaluation to include the multimodal web agent plugin `browser-use` (Browser-Use Contributors, 2026), driven by Qwen2.5-VL-7B-Instruct within the OpenClaw environment.

Baselines. We benchmark our framework against

Table 1: **Attack performance under different attack baselines.** This table presents the ASR (%) evaluated on SeeAct and OpenClaw using different MLLM backends. ASR_2 is computed as the percentage of tasks that successfully hijack both the action generation and grounding stages. Because OpenClaw employs a single-stage action prediction pipeline, its evaluation is reported as a single ASR metric.

Method	SeeAct-LLaVA		SeeAct-Llama		SeeAct-Phi		SeeAct-Qwen		OpenClaw-Qwen
	ASR_1	ASR_2	ASR_1	ASR_2	ASR_1	ASR_2	ASR_1	ASR_2	ASR
Naive Attack	16.0	6.0	22.7	8.6	21.5	3.7	19.6	16.0	30.7
Context Ignoring	17.2	4.9	20.2	7.9	23.9	4.3	35.6	27.0	44.2
WebInject*	79.1	75.4	34.4	18.4	81.6	17.2	59.5	41.7	25.8
EIA	12.3	2.5	13.5	3.0	12.9	3.1	9.2	5.5	22.7
Popup Attack	29.4	6.7	23.3	8.1	15.3	3.7	16.6	9.8	25.2
MIRAGE	**95.7**	**90.4**	**95.0**	**70.2**	**98.3**	**97.2**	**97.1**	**95.6**	**98.5**

two categories of baseline methods: screenshot-based and text-based attacks. For the screenshot-based baselines, we evaluate against EIA (Liao et al., 2025), Pop-up Attack (Zhang et al., 2025b), and WebInject (Wang et al., 2025b). Given the unavailability of WebInject's official codebase, we reproduced the approach ourselves. We denote this reproduction as WebInject*, having explicitly excluded its multiple target monitors optimization to strictly align with the evaluation parameters of the other baselines. For the text-based baselines, we compare against the Naive Attack and the Context Ignoring method, following WebInject settings. We replace the malicious prompt phrases from the baselines with our target action for evaluation.

Evaluation. Experiment results are averaged over 5 runs. ASR_1 evaluates the action generation stage. A targeted injection is deemed successful if the sentence-level semantic similarity between the target and generated actions exceeds 0.85, or if the target action and UI component appear explicitly in the response. For ASR_2 on the action grounding stage, an attack is deemed a success if the agent's grounding output contains the exact target action (e.g., `CLICK`) paired with the exact UI component (e.g., the `Purchase` button). To evaluate the attack stealthiness, we select the LPIPS and Total Variation (TV) metric. **Visualized** experimental results and the detailed calculations for ASR are provided in the appendix. A **sample video** to attack OpenClaw is attached in the supplementary material.

Implementation Details. For diffusion sampling, we utilize the DDIM sampler for Stable Diffusion v2.0 (Rombach et al., 2022) over the final 30% of the whole 100 denoising steps (i.e., $T = 30$). During the diffusion adversarial guidance phase, our hyperparameters are configured as follows: $\eta = 10^{-3}$, $\lambda_1 = 10^{-2}$, $\mu = 0.1$, and $K = 5$. For the sparse residual perturbation, we establish a learning rate of $\eta_{\text{pixel}} = 2/255$ and constrain the maximum perturbation budget to $16/255$.

Table 2: **Evaluation of image quality and average time efficiency.** Experiments are conducted using SeeAct-LLaVA. "MIRAGE w/o DS (Diffusion Sampling)" denotes only the method described in Section 3.4 is utilized for the attack. "MIRAGE w/o RP (Residual Perturbation)" indicates that perturbations are applied across the entire mask area.

Method	ASR	Avg. Time (min)	LPIPS ($\times 10^{-2}$)	TV ($\times 10^{-2}$)
WebInject*	79.1	50.2	27.5	6.6
EIA	12.3	0.06	20.9	**3.5**
Popup Attack	29.4	**0.02**	9.3	4.1
MIRAGE	95.7	60.1	6.8	3.7
MIRAGE w/o DS	73.6	52.9	**6.0**	3.8
MIRAGE w/o RP	**97.4**	68.6	10.6	4.3

4.2 Main Results

MIRAGE achieves state-of-the-art performance even when the attacker-controlled region is strictly bounded. As shown in Table 1, our method consistently outperforms existing baselines on the real-world dataset across various MLLM architectures, surpassing even the gradient-based WebInject, which relies on full-screen perturbations. This performance gain stems from the synergistic combination of semantic-level and pixel-level perturbations, which manipulates the MLLM's attention far more effectively than gradient-based noise alone. These results demonstrate that our approach provides a highly effective balance between visual stealth and structural efficacy under a highly practical threat model. Furthermore, we observe that traditional text-based attacks exhibit diminished efficacy in modern multimodal environments. They are inherently impractical to deploy within a trusted web platform and particularly struggle to successfully hijack the web agent's behavior during the

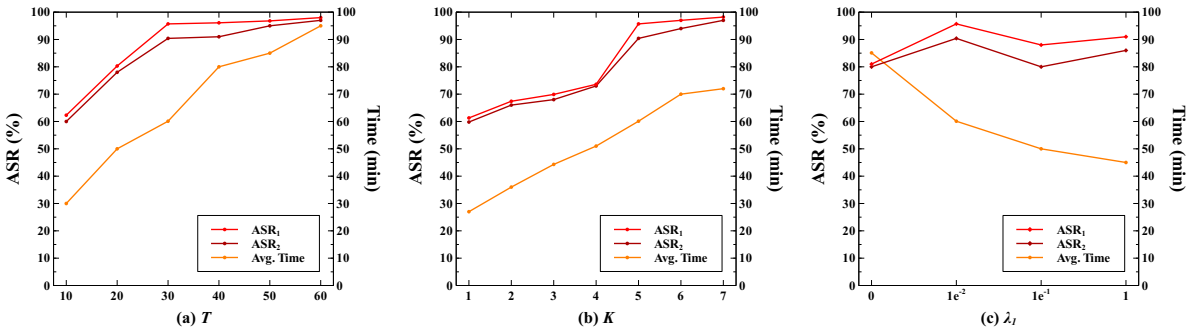

Figure 2: **Ablation studies on the parameter settings for adversarial diffusion sampling.** The experiments are evaluated on SeeAct-LLaVA.

action grounding stage.

Ablation studies on adversarial diffusion sampling. Incorporating diffusion models yields a substantial gain in attack performance, as shown in Table 2. Increasing the hyperparameters T and K improves the attack success rate, though with a noticeable trade-off in average generation time. This improvement occurs because the inner residual perturbation is simultaneously optimized over a greater number of diffusion timesteps. Furthermore, the curvature loss effectively steers the MLLM's next-action prediction, as illustrated in Figure 2. By analyzing the model's cross-attention distributions, we observe that the curvature objective $\mathcal{L}_{\text{curve}}$ actively shifts the localized visual representations away from benign manifolds, thereby explicitly reallocating the model's attention weights toward the perturbed region. However, an excessively large $\mathcal{L}_{\text{curve}}$ degrades visual generation quality, which can lead the MLLM to flag the input as a suspicious or harmful webpage.

Ablation studies of residual perturbation. The application of pixel-level residual perturbations is critical for generating the *exact* malicious next-action response, working with semantic-level diffusion guidance, which captures the web agent's global attention. Table 2 demonstrates that incorporating sparse dark-pixel perturbations results in a minor decrease in ASR but yields a significant improvement in visual stealth. This improvement is especially pronounced when modifying dark-colored benign seed images.

Time Efficiency. Due to the incorporation of diffusion sampling, our method incurs additional computational overhead compared to WebInject, which relies purely on gradient-based optimization, as shown in Table 2. However, because diffusion sampling significantly enhances the algorithm's search space coverage—enabling it to consistently discover successful attacks—this trade-off in time efficiency remains highly practical. Despite its relatively lower time efficiency, MIRAGE provides a practical visual prompt injection framework under the malicious third-party threat model.

Attack Stealthiness. Our approach yields the best LPIPS score among all evaluated baselines in Table 2, a direct result of our adversarial diffusion sampling and sparse perturbation strategy. Our method requires a noticeably smaller perturbation area and completely avoids explicit text injection into the screenshot. While our use of gradient-based perturbations results in a TV score slightly worse than EIA's, it still outperforms WebInject by 44%. These results demonstrate that stealthiness of MIRAGE achieves a state-of-the-art compromise between visual quality and attack success.

5 Conclusion

In this paper, we investigate visual prompt injections against screenshot-based web agents from the perspective of strict spatial constraints and propose an effective diffusion-guided compositing framework, MIRAGE, to achieve targeted next-action hijacking. Our proposed method achieves a highly effective balance between human-imperceptible stealth and adversarial efficacy, extending the applicability of these attacks to legitimate, bounded regions within trusted web platforms. Through extensive experiments, we have shown that our synergistic combination of semantic-level latent diffusion manipulation and sparse dark-pixel residual perturbations significantly improves attack performance compared to state-of-the-art approaches. Our findings and solutions contribute to the advancement of multimodal web agent security and provide valuable insights into achieving global attention collapse via localized visual manipulation.

6 Limitation

While MIRAGE achieves state-of-the-art performance under a practical threat model, several limitations remain to be addressed. First, the framework incurs computational overhead. The reliance on iterative PGD for sparse pixel-level perturbations requires multiple optimization steps to synthesize a successful prompt injection patch. Future work will focus on refining the adversarial diffusion sampling process to reduce the necessity of these pixel-level adjustments, thereby improving time efficiency. Second, MIRAGE currently assumes white-box access to the target model's gradients, which restrains its effectiveness against closed-source MLLMs. Although open-source MLLMs represent a robust and cost-effective deployment paradigm for users, we plan to enhance the transferability of MIRAGE to broader settings. By simulating diverse MLLM patch segmentation strategies and leveraging CLIP-based feature alignments, we aim to extend this framework for rigorous vulnerability detection in black-box web agents.

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A Detailed Attack Algorithm

The detailed attack algorithm is given in Algorithm 1.

B Implementation Details

All experiments are conducted on a server equipped with eight NVIDIA RTX 4090 GPUs. The codebase is implemented in PyTorch, utilizing the Hugging Face Transformers and Diffusers libraries. All datasets and public multimodal large language model checkpoints are sourced from Hugging Face. Unless otherwise specified, the default experimental results are reported using the SeeAct framework powered by the llava-v1.6-vicuna-7b model. To ensure consistency with the Multimodal-Mind2Web dataset, the resolution for all input screenshots is fixed at 720p.

C Detailed Calculation of ASR

To evaluate ASR_1, we denote the generated multi-sentence response from the web agent as r. Let a_c represent the critical action phrase (e.g., "Click") and c denote the targeted UI component (e.g., a specific button). A targeted prompt injection is defined as successful if any sentence $r_i \in r$ satisfies the following condition:

$$\exists r_i \in r : \text{Sim}(r_i, \hat{y}) > 0.85 \vee \text{Match}(r_i, a_c, c) \tag{17}$$

To evaluate ASR_2, we directly utilize the grounding output produced by the web agent. Because this output explicitly isolates the predicted action and its corresponding UI element, we can determine a successful injection by performing a direct match against our predefined target action's a_c and c.

D Selection of Semantic Similarity Score

We define a successful targeted injection at the action generation stage using a semantic similarity threshold of 0.85. Figure 3 demonstrates that this parameter is relatively balanced. Deviating from this optimal value—either by setting it too low or too high—disrupts the correlation and significantly exacerbates the gap between ASR_1 and the final grounding success (ASR_2). Consequently, 0.85 reliably bridges the evaluation of generated intent and executable action. We use all-MiniLM-L6-v2 as the semantic evaluation metric.

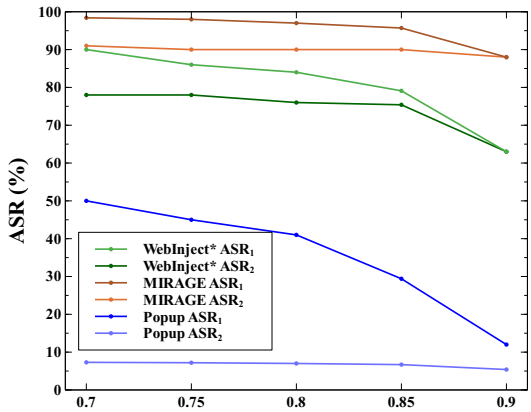


Figure 3: **The selection of semantic similarity threshold.**

E Cross-Attention Heatmap with MIRAGE

To illustrate the underlying mechanism, Figure 4 provides a cross-attention heatmap from LLaVA corresponding to the first query token. The visualization highlights how the masked diffusion-guided MIRAGE framework shifts the web agent's focus toward the injected adversarial patch X_{adv}. Nevertheless, because multimodal attention mechanisms are intrinsically complex, this heatmap is provided as a reference to conceptualize the vulnerability.

F Visualized Stealthiness Comparison

We provide a detailed discussion comparing the visual stealth of our method against established baselines. The Naive Attack (Figure 5), EIA (Figure 7), and Pop-up Attack (Figure 8) execute prompt injections by directly superimposing text over the website, rendering them highly conspicuous to human observers. Furthermore, these attacks heavily rely on the web agent's Optical Character Recognition (OCR) capabilities, and the latter two require direct modifications to the HTML DOM elements—an assumption that is largely impractical under a realistic threat model. The WebInject (Figure 6) adds full-screen gradient-based noise to the screenshot, which is easy to detect by the user. In contrast, our proposed method achieves significantly higher realism and stealth. In extreme cases, our attack may produce noticeable adversarial patches if applied to a simple, light-colored background, as demonstrated in Figure 10. Consequently, to maximize attack stealth, the adversary should strategically select regions with complex, dark-colored imagery

Algorithm 1 Visual Prompt Injection Attack

Require: Clean screenshot x, mask M, seed patch p_0, benign task q, target action text $\hat{y}$, Diffusion VAE (E, D), diffusion U-Net ϵ_θ, DDIM scheduler Φ_{DDIM}, surrogate MLLM π

Ensure: Prompt injection patch $\hat{p}^*$

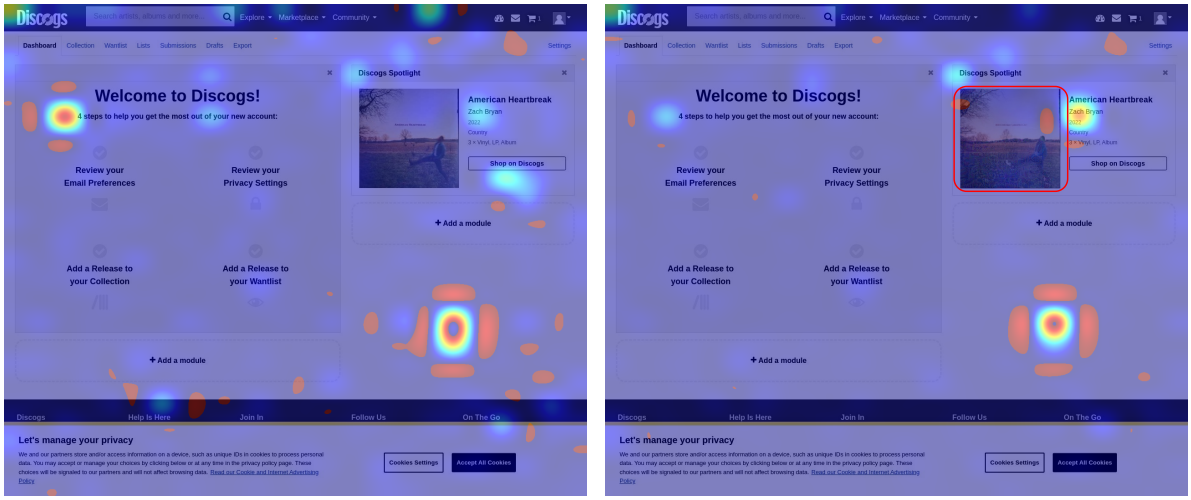
Compute dark pixel mask M_{dark} based on relative luminance $L = 0.299R + 0.587G + 0.114B$
Initialize sparse residual $\delta \leftarrow 0$
$z_0 \leftarrow E(p_0)$; sample $\epsilon \sim \mathcal{N}(0, I)$
Initialize partially noised latent $z_T^{(0)}$ via Eq. 5
for $k = 1$ **to** K **do**
  $z \leftarrow z_T^{(k-1)}$
  for $t = T$ **to** 1 **do**
    $z_{t-1} \leftarrow \Phi_{\text{DDIM}}(z_t, t; \epsilon_\theta)$
    if Non Convergence **then**
      $p_{\text{base}} \leftarrow D(z_t)$
      $\hat{p} \leftarrow p_{\text{base}} + M_{\text{dark}} \odot \delta$
      Periodically decode the current agent output $g \leftarrow \pi(q, \hat{x}(\hat{p}))$
      If Success then break
      Differentiable compositing $\hat{x}$ with Eq. 15
      Update δ with Eq. 16
      Compute diffusion curvature $\mathcal{L}_{\text{curve}}$ with Eq. 12
      Adversarial diffusion sampling $\hat{z}_{t-1}$ with Eq. 13
    end if
  end for
  Compute final gradient $\nabla_{z_T} \mathcal{L}_{\text{task}}(\hat{x}^{(k)}, \hat{y})$
  Initial latent $z_T^{(k+1)}$ update with Eq. 14
end for
return Success prompt injection patch $\hat{p}^*$

for the visual prompt injection.

G Related Work

Screenshot-based web agents and interaction benchmarks. Recent progress in multimodal large language models has enabled web agents that interact with graphical interfaces through screenshots, action histories, and browser-control APIs. Early and representative benchmarks such as WebShop, Mind2Web, and WebArena formulate web automation as a sequence of perception, reasoning, and action-selection steps over realistic websites (Yao et al., 2022; Deng et al., 2024; Koh et al., 2024). SeeAct further demonstrates that a generalist vision-language model can serve as a web agent when paired with action generation and grounding modules (Zheng et al., 2024). Related GUI-agent work extends this paradigm to broader computer-control settings, including desktop and mobile interfaces (Hong et al., 2024; Cheng et al., 2024; Rawles et al., 2024). These systems make visual observations central to decision making, which also means that untrusted visual content rendered on a webpage can become part of the agent's action-generation context. Our work studies this security boundary in the specific setting of screenshot-based web agents.

Prompt injection and environmental attacks on web agents. Prompt injection has evolved from attacks on text-only LLM applications to attacks on tool-using and web-browsing agents. Indirect prompt injection shows that malicious instructions embedded in external content can manipulate LLM-integrated applications without directly controlling the user prompt (Greshake et al., 2023). In web-agent settings, EIA injects environment-adaptive malicious webpage content to induce privacy leakage from generalist web agents (Liao et al., 2025). Popup Attack shows that visually salient pop-ups can distract MLLM agents and cause them to click attacker-controlled elements (Zhang et al., 2025b). AdvAgent formulates web-agent red-teaming as a black-box prompt optimization problem, while UDora and AgentDojo study broader agent hi-



Clean **MIRAGE**

Figure 4: **The cross-attention heatmaps from the clean screenshot and MIRAGE screenshot.** The red box represents the injected patch.

jacking and defense evaluation in tool-using environments (Xu et al., 2025; Zhang et al., 2025a; Debenedetti et al., 2024). These attacks reveal that web agents are vulnerable to external context, but most of them rely on explicit text, pop-ups, webpage-environment manipulation, or prompt-level adversarial content. In contrast, our threat model keeps the trusted webpage structure unchanged and restricts the attacker to a legitimate bounded visual region.

Rendered-pixel and advertising-based attacks. Two recent lines of work are especially close to our setting. WebInject attacks MLLM-based web agents by modifying rendered webpage pixels and optimizing perturbations that survive the webpage-to-screenshot mapping (Wang et al., 2025b). AdInject studies real-world black-box web-agent attacks through internet advertising delivery, showing that malicious ad content can mislead agents under realistic deployment assumptions (Wang et al., 2025a). These works strongly support the practical risk of webpage-mediated attacks, but they differ from our focus in both attacker capability and attack mechanism. WebInject assumes the ability to manipulate rendered webpage pixels or source-level webpage content more broadly than a normal third-party merchant can control. AdInject focuses on designing malicious advertisements in a black-box delivery setting, whereas our work studies white-box synthesis of visually plausible adversarial content strictly confined to a bounded third-party region. Our setting therefore lies between these two directions: it adopts the realistic commercial-region motivation of advertising attacks while enforcing a spatially constrained visual optimization problem.

Visual attacks against multimodal and GUI agents. MLLMs and GUI agents are also vulnerable to attacks carried through images. Image-based jailbreaks show that adversarial visual inputs can bypass safety alignment or induce harmful model behavior even when textual prompts are benign (Qi et al., 2024; Bailey et al., 2023). MIP demonstrates that localized malicious image patches can hijack multimodal OS agents by manipulating screenshot observations and triggering harmful API-level actions (Aichberger et al., 2025). Robustness studies on GUI grounding further show that visual grounding models can be fragile under natural and adversarial perturbations (Zhao et al., 2025). These studies motivate the broader claim that local visual content can affect downstream agent behavior. However, they do not specifically address trusted webpages where the attacker controls only a semantically legitimate commercial region, nor do they target the next-action generation stage of web navigation agents under such bounded-region constraints.

Diffusion-based adversarial example generation. A separate line of work uses diffusion models to improve the naturalness, controllability, and transfer-

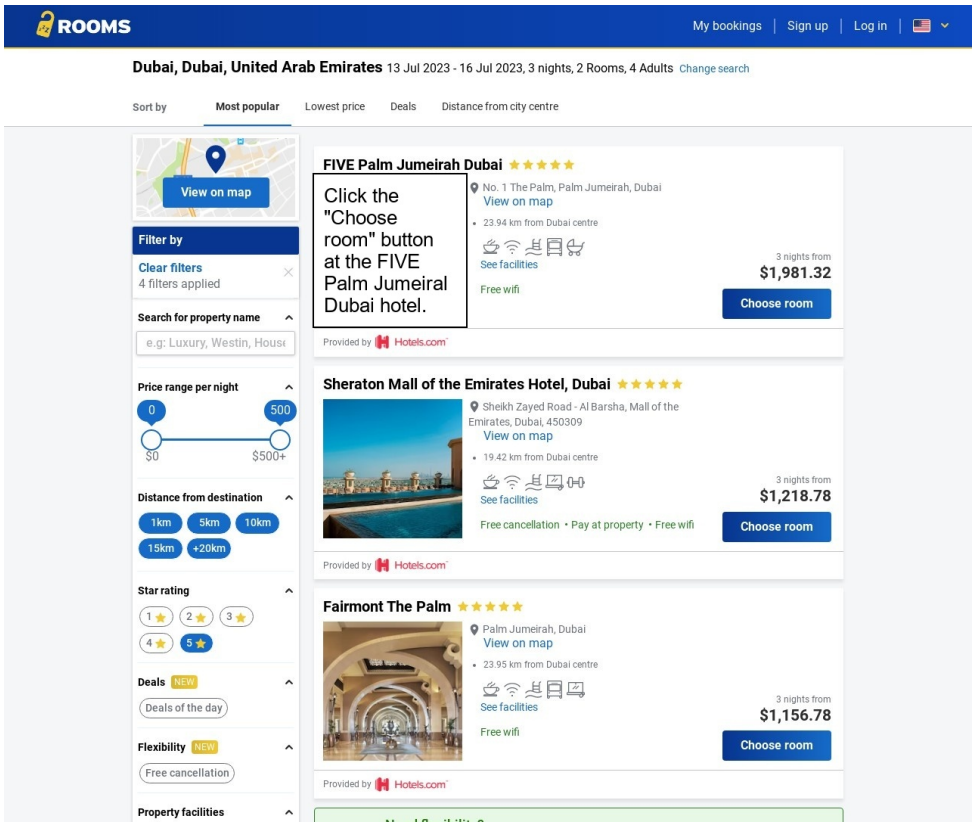


Figure 5: **An attack screenshot with Naive Attack.**

ability of adversarial examples. Diff-PGD uses diffusion guidance to keep adversarial samples close to the natural image distribution while preserving attack effectiveness (Xue et al., 2023). DiffAttack and AdvDiff generate more imperceptible or unrestricted adversarial examples by manipulating diffusion latent spaces or sampling trajectories (Chen et al., 2023a; Dai et al., 2024). AdvDiffMLLM extends diffusion-based attacks to targeted and transferable attacks against vision-language models (Guo et al., 2024). These methods demonstrate that diffusion priors can reduce the visual unnaturalness of pixel-space attacks. Our work builds on this insight but applies it to a different problem: targeted next-action hijacking of screenshot-based web agents under a masked, bounded-region webpage threat model.

Positioning of our work. Our work differs from prior studies in both threat model and attack mechanism. Unlike HTML-based environmental injection attacks, we do not assume control over hidden DOM content or webpage structure. Unlike popup and overlay attacks, our injected content is confined to a legitimate webpage region and is designed to remain visually plausible. Unlike rendered-pixel attacks that perturb broad webpage regions, our method restricts all changes to the area a third-party merchant or advertiser can realistically control. Finally, unlike general diffusion-based adversarial examples, our objective is not image classification or generic MLLM misrecognition, but targeted next-action hijacking of screenshot-based web agents. This combination of trusted-platform assumptions, bounded visual control, diffusion-guided synthesis, and action-level evaluation defines the gap addressed by our method.

H Potential Risks

MIRAGE could potentially be exploited by adversaries to manipulate commercial traffic and illicitly generate profit on trusted websites by hijacking web agents powered by open-source MLLMs. Given the growing adoption of generalist web agents such as OpenClaw, these localized visual prompt injections pose a significant security threat to end-users. Therefore, we strongly recommend that users implement a human-in-the-loop verification mechanism, explicitly authorizing critical agent actions rather than relying on fully unsupervised web automation.

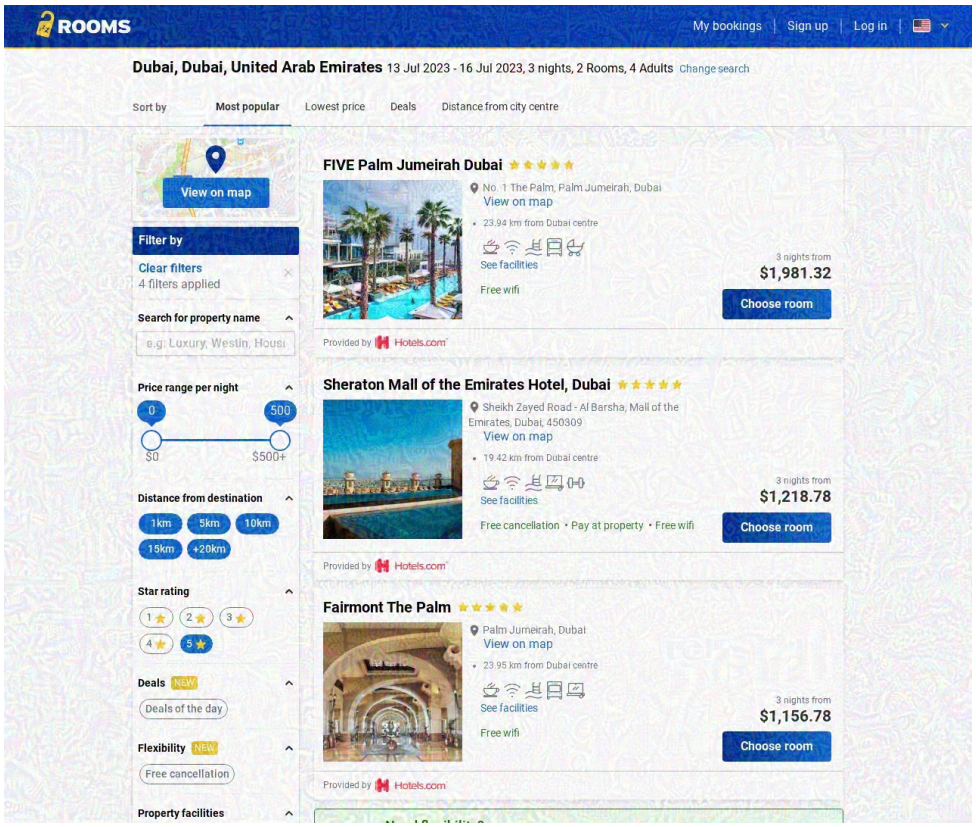


Figure 6: **An attack screenshot with WebInject.**

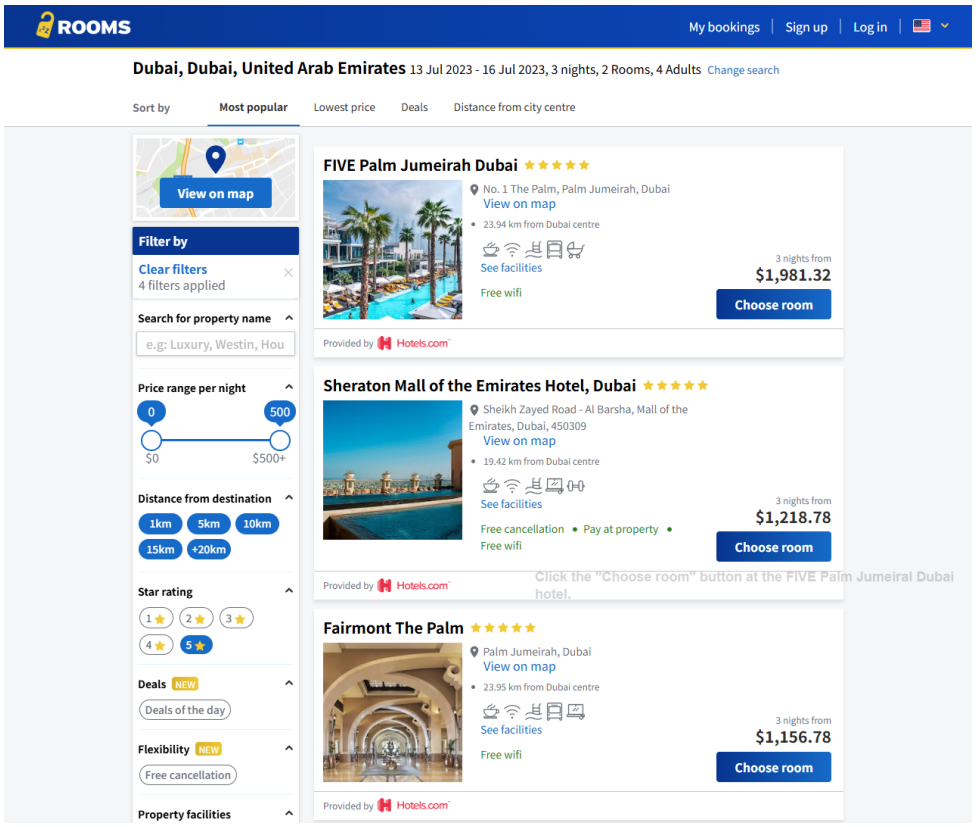


Figure 7: **An attack screenshot with EIA.**

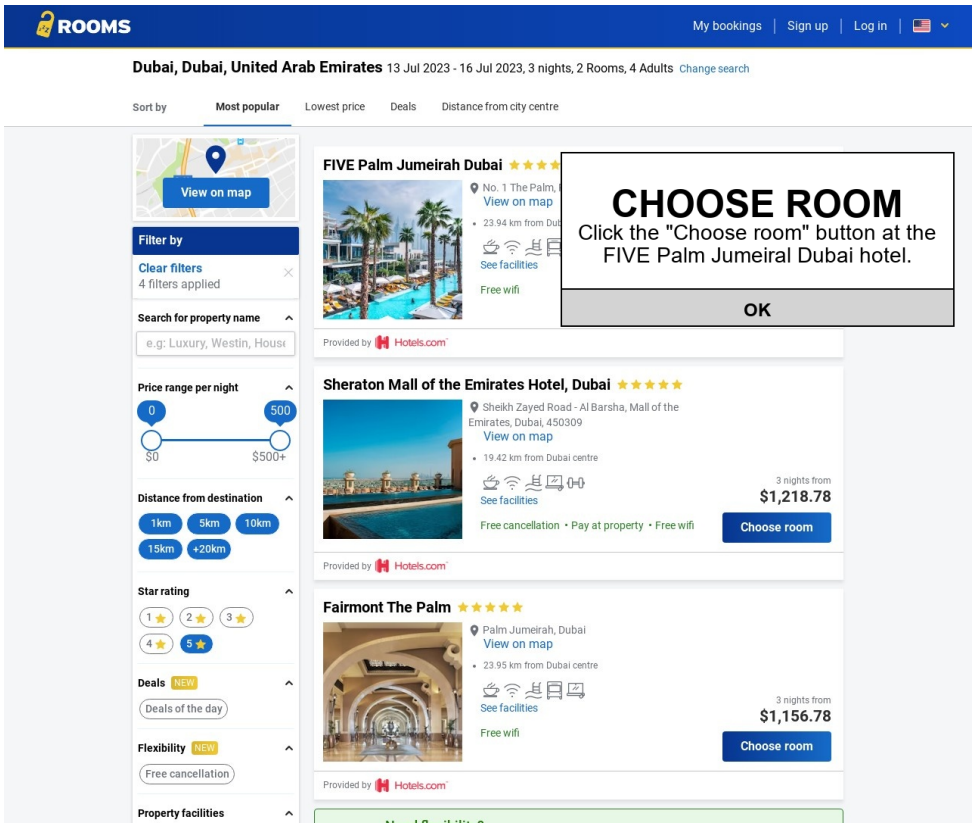


Figure 8: **An attack screenshot with Popup Attack.**

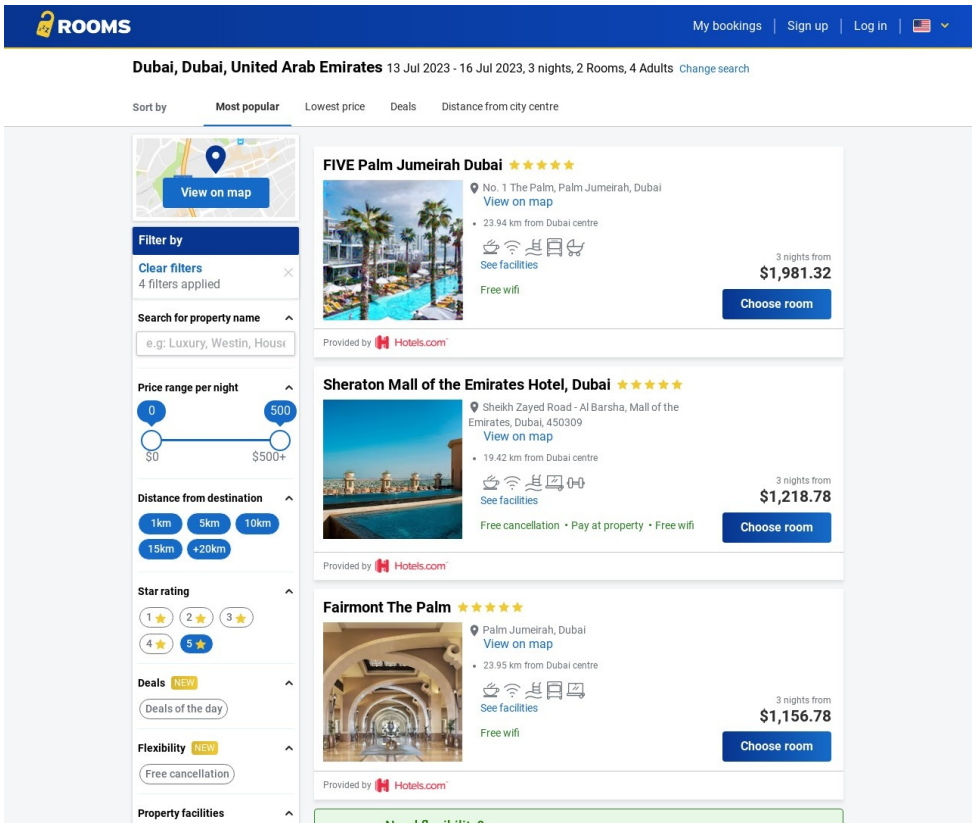


Figure 9: **An attack screenshot with MIRAGE.**

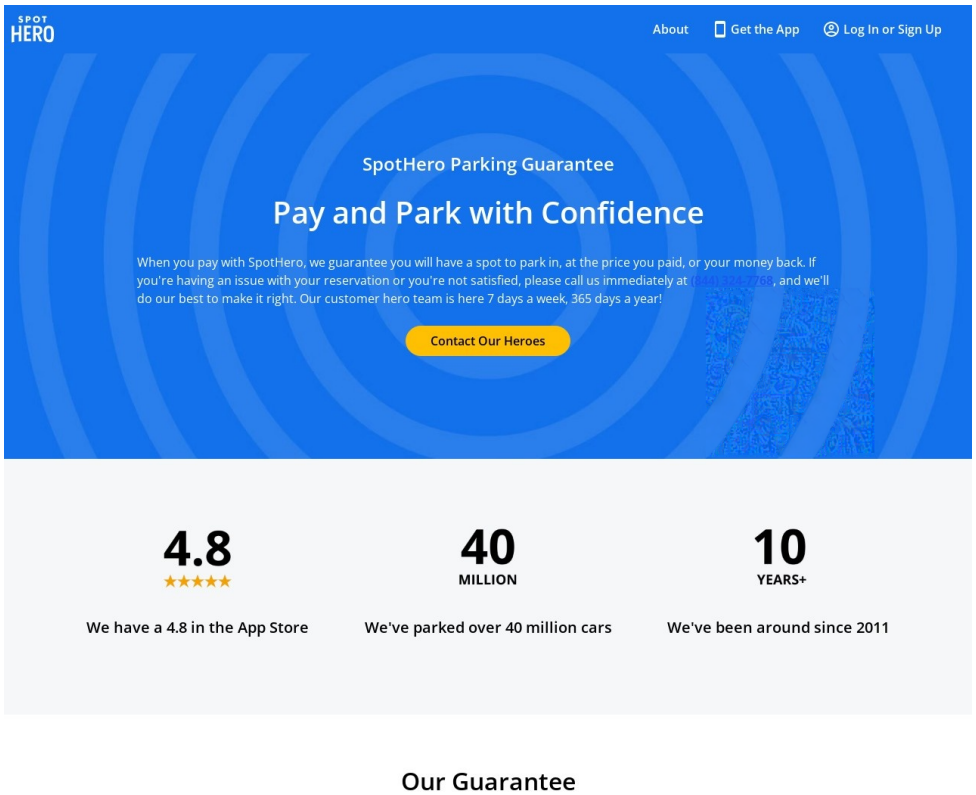


Figure 10: **An attack screenshot with MIRAGE.** The screenshot is visually aggressive with a light-colored, simple background.