Using Context and Interactions to Verify User-Intended Network Requests

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Abstract—Client-side malware can attack users by tampering with applications or user interfaces to generate requests that users did not intend. We propose Verified Intention (VInt), which ensures a network request, as received by a service, is user-intended. VInt is based on “seeing what the user sees” (context). VInt screens the user interface as the user interacts with a security-sensitive form. There are two main components. First, VInt ensures output integrity and authenticity by validating the context, ensuring the user sees correctly rendered information. Second, VInt extracts user-intended inputs from the on-screen user-provided inputs, with the assumption that a human user checks what they entered. Using the user-intended inputs, VInt deems a request to be user-intended if the request is generated properly from the user-intended inputs while the user is shown the correct information. VInt is implemented using image analysis and Optical Character Recognition (OCR). Our evaluation shows that VInt is accurate and efficient.

I. INTRODUCTION

Our society is increasingly reliant on online services to perform daily tasks, ranging from online banking, messaging, and even the management of household appliances. Due to the increasing functionality provided by these services and their sensitive nature, they can be a lucrative target for malicious actors. A common target is the communication channel between the user making the service request and the server machine in the “cloud” processing and fulfilling it. Malicious tampering with this channel can result in a variety of harmful attacks, including hijacked bank transfers or the impersonation of an unsuspecting user.

We break the user-server channel into two segments: user-machine and machine-machine. The security of the communication channel between the user’s client machine and the server machine has been explored in-depth, through hash functions, checksums, and authentication protocols such as TLS. However, an often overlooked component is the communication channel between the human user making the service request and their own machine that processes the request, which can be compromised and make malicious requests on behalf of the user without detection by the remote server machine. Similar to the machine-machine channel, the integrity and authenticity of this channel are integral to the online service model.

A primary challenge in securing the human-machine communication channel is that it is asymmetric in nature and must handle user input on one end and computer output on the other. Unlike the machine-machine channel, which is symmetric and whose integrity and authenticity can be verified using the same methods in both directions, securing the human-machine channel requires protecting the integrity and authenticity of both the rendering of computer output to the user, as well as the processing of user inputs by the computer. In this work, we aim to secure this human-machine interface using user intention. Specifically, we deem user inputs to be user-intended when integrity and authenticity are achieved in both directions (input and output). A network request is user-intended if it is securely generated from user-intended inputs.

Prior works on securing the human-machine channel lack complete integrity or authenticity guarantees. NAB [1] and Binder [2] infer user intention through heuristics, and provide neither input nor output integrity and authenticity. Gyrus [3] provides input integrity and authenticity by asking the human user to confirm inputs shown on the display, but it provides no guarantee on the computer output. Recent works [4]–[6] point out that input integrity does not hold alone unless output integrity is also achieved, as human users may be fooled by attacker-generated deceptive content and give unintended inputs. However, these works protect a simplified rendering engine inside some secure software module and only provide output integrity guarantee for a subset of the user interface. Despite the extra user effort required to distinguish protected content from unprotected content on the same screen, the fact that not the entire screen is protected enables new attacks.

The lack of complete output integrity allows an attacker to send out user unintended requests. Inspired by prior user interface (UI) attacks such as clickjacking [7], [8], we identify a new class of user interface attack that we call “context forgery,” where an attacker tricks the user into sending out unintended requests through a luring and deceptive user interface (i.e. the “context”). Different from clickjacking, which causes unintended actions locally, context forgery aims to lure the user into sending out unintended requests to a remote service. In particular, we account for malicious actors that have OS-level privilege on the user’s machine and that attack the browsers platform on x86 architecture. This combination is chosen because it is the hardest case of having to defeat a context forgery attack.

We propose four variations of context forgery attacks that violate output integrity and authenticity and cause unintended
In this paper, we make the following contributions:

- Accuracy and negligible performance in most cases.
- Base (TCB), reducing the potential attack surface. We evaluate against our proposed attacks with a minimal trusted computing environment (TEE), such as Intel SGX [13] and Arm TrustZone [14], for user-level malware.

Our solution. We propose Verified Intention (VInt), a framework for capturing semantic-rich user intentions and protecting a service from unintended requests. VInt aims to achieve full integrity and authenticity of the human-computer channel, which prior works provide partially. Our method is based on the observation that network requests originate from a specific context and we can ensure integrity and authenticity by observing this context. VInt captures the context by taking continuous screenshots of user interactions while the user interacts with a security-sensitive website. To achieve output integrity and authenticity, VInt checks whether the user was shown the correct text and images; to achieve input integrity and authenticity, VInt refers to the human user by correlating hardware IO with on-screen activities — we assume the user ensures that on-screen user-provided inputs are user-intended through a “what you enter is what you wanted (WYEIWyW)” principle: inputs vetted by the human user are integrity- and authenticity-protected. VInt ensures that an actual human is present by checking hardware IO events, which can only be performed by a physical human. With full input and output integrity and authenticity, user-provided inputs represent user intention because the user provided them after shown the proper information.

We implement VInt in a secure virtual machine (VM) on Xen using OpenCV image analysis and Tesseract Optical Character Recognition (OCR). We show that VInt can defend against our proposed attacks with a minimal trusted computing base (TCB), reducing the potential attack surface. We evaluate VInt on 119 web pages, and show that VInt achieves high accuracy and negligible performance in most cases.

In this paper, we make the following contributions:

- We identify a set of context forgery attacks that can send out user unintended requests solely by violating the output integrity and authenticity.
- We propose the use of context (screenshots of the user interactions with a web page) to verify user intentions, securing the integrity, authenticity of the input and output of the human-machine channel.
- We show that VInt can defeat proposed context forgery attacks, obtain a 98.2% accuracy and require only 0.165 seconds in 1920 by 1080 resolution in most cases on 119 commercial web pages.

II. DEFINITIONS AND PROBLEM STATEMENT

A. Definitions

We define the following concepts related to our work:

- Machine output: The content shown on the Graphical User Interface (GUI). We refer machine output to just output in the rest of the paper.
- User input: The physical inputs a user gives to the computer and the machine’s processing of those inputs. We refer user input to just input in the rest of the paper.
- Input integrity and authenticity: when the user inputs are processed correctly (integrity) from the proper source (authenticity).
- Output integrity and authenticity: when the machine output is rendered correctly without an attacker’s inference (integrity) from the proper source (authenticity).
- User intended inputs: the inputs a user gives to the machine under with integrity and authenticity guarantees of both input and output.
- User intended requests: a request that is properly generated based on user intended inputs.

B. User-impersonating Attacks

We discuss the user-impersonating attacks that we address in this paper. We show how we classify user-impersonating attacks as either request forgery or context forgery. We show examples of user-impersonating attacks.

1) Attack Definitions: Malware can craft network requests to a remote service without the user’s awareness. This type of attack is called a user-impersonating attack [4], as the service is not able to distinguish whether a request is malware-generated or human-intended. User-impersonating attacks have demonstrated their effectiveness in stealing money [9], fake user ads clicks [10] and usage fraud [11].

User-impersonating attacks can be launched by attackers at various levels. Similar to prior works [1], [3]–[6], [12], this work assumes an OS-level attacker on the web browser platform. An OS-level malware is the hardest to defend against due to its privilege, which can be used to hide its presence and access unprotected memory. We work with browsers as 1) they are applicable to both desktop and mobile platforms, 2) they suffer from a rendering variation problem (§III-D) and 3) the remote service has the least control over them. For applications, the service can incorporate defenses that are not available for web pages. For instance, Trusted Execution Environments (TEE), such as Intel SGX [13] and Arm TrustZone [14], for user-level malware.

We classify user-impersonating attacks into two types: request and context forgery. Request forgery is when a request is created or existing requests are changed without a user’s awareness. For instance, malware can forge a money transfer request to the attacker’s PayPal account [9]. Prior works [3]–[6], [12] provide input integrity and authenticity to defeat these attacks through secure IO and request generation. The more interesting attack, which is also the focus of this paper, is context forgery. Context forgery is when an attacker presents a misleading user interface to lure users to perform actions that send out unintended requests. Prior works do not defeat against context forgery due to the lack of full output integrity.

Attack Model. When an attacker attempts to tamper with the IO data flow [15]–[18] or tamper with the execution integrity of the request generation [19], he violates the input integrity, authenticity, or execution integrity of the request, for which we refer to as a request forgery attack. When an attacker attempts to tamper with the local user interface (UI) similar to prior works [7], [8] and does not violate any properties in a request forgery attack, he violates output integrity or authenticity, for which we refer to as a context forgery attack. Although a
context forgery attack does not require OS-level privilege, an OS-level malware still has the ability to modify UI.

2) User-impersonating Attack Examples: We focus on the design aspect of attacks than the implementation side.

Request Forgery. There are two variants of request forgery. 1) Forgery: an attacker can forge a request without the user’s awareness. For instance, an attacker in the early form submission attack proposed in ProtectION [6] emulates a mouse click before the user completes the form, which results in an incomplete and thus unintended request being generated. 2) Tampering: an attacker tampers with user inputs to a request or the execution integrity of the request to send out user-unintended requests. For instance, parameter tampering attack [20] violates the integrity of user inputs.

Context Forgery. To show context forgery attacks, we break UI elements into two types: service and host depending on who owns the elements. Service-owned elements include all elements on the web page itself, which were sent from the service, while host-owned elements include the display of user inputs, cursor and the browser toolbars. Therefore, context forgery attacks can be split into three types: service UI tampering, host UI tampering and temporal integrity violation.

Variant #1 and #2: Service UI Tampering. The attacker tampers with the user interface rendered from data owned by the service. The user may be tricked into believing that the page comes from the service. There are two variants: 1) minimum area (Fig 7): the attacker modifies a small region of the UI, hoping the user will not notice. The attacker can indirectly tamper with the request if the human user relies on the tampered information in generating the request. 2) context hiding (Fig 1): certain UI elements may prevent UI overlays, therefore, the attacker can craft all other UI elements and expose only the protected ones, giving the user a misleading crafted context. This attack can be applied to works [4]–[6] with an embedded secure window.

Variant #3: Host UI Tampering. The attacker tampers with the UI elements owned by the local system. Examples of host UI elements include the display of textual inputs, the mouse cursor and the browser toolbars. Due to the fact that these UI elements are owned by the local host, there is no ground truth to validate the appearance against. An attacker can modify the host UI and trick the user into having an incorrect perception of the state of the machine and generating requests from an unintended system state. An example is illustrated in Fig 2.

Variant #4: Temporal Integrity Violation. An attacker can exploit defenses by violating the temporal integrity of the user interface. Instead of tampering with the existing content of the interface, the attacker overlays a new element but exploits the asynchrony between when the user perceives an element on the screen and when they act and provide input to the machine in response to the element. An example is illustrated in Fig 3.

C. Discussion

The root cause of context forgery attack is that the semantics of the user interface are being tampered with. Specifically, text and images carry heavy semantics, and an attacker must modify them so the user perceives them differently.

We show how prior works handle context forgery attacks in Table I. We put a red cross when a prior work is vulnerable. From left to right, we see improving progress in securing the human-machine channel. Prior works range from providing no guarantee at all (NAB [1] and Binder [2]), to input integrity (Gyrus [3]), to weak output integrity (secured confirmation page does not suffice, as 1) the UI is not secured while the user perceives, the user may confirm unintended requests and 2) the fixed time interval can be exploited by an attacker by showing a series of pop-up windows mimicking the appearance of the real confirmation window, hoping that the user will spam clicks on the “yes” button and will not notice the content in the real pop-up window.

Observation 1: Input integrity will not hold unless output integrity is also achieved. Without output integrity, one cannot infer the circumstance that the user entered the inputs — the user might be fooled perceptually when entering inputs. Minimum Tampering attack can bypass these defenses to send out unintended requests.

Observation 2: Full output integrity must be enforced. Securing a subset of the user interface means that the user will still perceive from unprotected UI elements. Despite the extra user effort to distinguish protected content, an attacker can still make use of the unprotected elements to fool the human user as shown by Context Hiding attack.

Observation 3: Output integrity must be maintained throughout the user’s interaction session. Displaying a fully secured confirmation page does not suffice, as 1) the UI is not secured while the user perceives, the user may confirm unintended requests and 2) the fixed time interval can be exploited by Temporal Integrity Violation attack.

Observation 4: visual: Dilemma between functionality richness and security for embedded window approaches. Fidelius [5] and ProtectION [6] achieve partial output integrity through export-and-secure: a simplified rendering engine is ported into a trusted module to ensure the correctness of the rendering output. To support rich rendering features, a rendering engine must have a large codebase, which means a large program needs to be secured. To achieve high security, the trusted computing base size must be small [21]. This dilemma limits the functionality in current works [5], [6] and is tied to their export-and-secure approach, which is unlikely to be
TABLE I: Comparison of VInt with other intention capture works on proposed user-impersonating attacks. n/a means the attack is not applicable. We address VButton [4] with VB-B and VB-W standing for the trusted button and secure pop up window approaches.

| User-impersonating Attacks | Violated Properties | NAB [1] | Gryus [3] | VB-B [4] | Fudelnis [5] | ProtectION [6] | VB-W [4] | VInt |
|----------------------------|---------------------|---------|-----------|---------|-------------|----------------|---------|-----|
| Request Forgery            |Forgery Tampering    |Authenticity |Input Integrity |X |✓ | ✓ | ✓ | ✓ | ✓ |
| Context Forgery            |Minimum Tampering    |Output Integrity |Full Output Integrity and Authenticity |X |✓ | ✓ | ✓ | ✓ | ✓ |
|                           |Context Hiding       |Host UI Tampering |Output Integrity |X |✓ | ✓ | ✓ | ✓ | ✓ |
|                           |Temporal Integrity   |Temporal Integrity |Output Temporal Integrity |n/a |n/a | n/a | ✓ | ✓ | ✓ |

- The hypervisor and the trusted VM (dom0) are mutually trusted by the service and the user and provide isolation of its memory from guests. This can be justified because 1) the hypervisor can attest its code integrity to the service after boot [28], 2) the hypervisor can be set up securely by the user at a trusted set-up time, and 3) its code can be publicly audited.
- The hardware, including the processor, chipset, and peripherals, is trusted.
- The hypervisor has the ability to intercept input events before a guest sees it. This is commonly available on recent processors with Intel VT and AMD V.
- Availability is not considered.

Web Pages. VInt is not designed to work with all web pages. VInt’s focus is to vet user intended requests, thus, VInt is primarily used on security-sensitive forms such as money transaction form. As a result, VInt assumes that a synchronous request will be generated when the user completes the form and that request will trigger security-sensitive actions on the service’s side. This assumption does not prevent web pages from sending asynchronous AJAX requests, but they are not validated.

Remote Service. VInt assumes a trustworthy and cooperative remote service. The service, along with any data from the service, such as HTML, CSS, and JavaScript are trusted. This excludes phishing attacks where the service is malicious. Phishing defenses and service authentication are orthogonal to our work and can be integrated. We also assume the service is cooperative in modifying its page to ease client-side operations as it is one of the main beneficiaries of VInt. This assumption is also common in prior works [5], [6] who require modification of page source code. The exact requirements include:

- For output integrity and authenticity: VInt requires the service to separate text from complex backgrounds, put text with different font sizes in different lines and ensure the absence of foreign languages. These requirements come from our evaluation in §VI-B2.
- For input integrity and authenticity: VInt requires the service to adopt a common design style of visual indicators using CSS, which include 1) a blue focus box (outline on focus) 2) a green non-blinking input cursor (caret) and 3) a blue selection color (selection:color). An example of the caret and the focus box are shown in Fig 4. VInt only supports textboxes and textareas, which need to be made large enough for the size of anticipated inputs. These requirements are discussed in §III-E.

We think many of these requirements are already met by security-sensitive forms, as one of their design principles is clearness and unambiguousness.

Human User. While the user interacts with the web page on her desktop, we assume the user does not perceive information solved with development in a secure software module or rendering engines.

Strawman Approaches. One strawman approach is to take a screenshot of a filled form after the user submits the form. Output integrity can be enforced by validating the rendering of the web page in the screenshot, while input integrity can be inferred from the displayed inputs from the screenshot.

This method has flaws. One time screenshot cannot satisfy R2, as temporal integrity is not maintained — an attacker can show one set of crafted UI to the user and quickly swap to a different set of legitimate UI before the screenshot is taken [22]. A video recording of the user interaction at fixed intervals, e.g. 30 frames per second, suffers from the same issue, as the attacker can swap contexts at every frame capture. Similarly, temporal integrity violation applies to inputs. Secondly, sending a screenshot of the user’s activity to a remote server raises privacy concerns. Lastly, it is unclear how a screenshot can be validated as prior shows that individual client renders the same content with variations [23]. A validation method must be 1) robust to allowable difference and 2) sensitive to tampering. Image hash [24] are designed for this task [25], but they are insufficient in terms of preciseness (not sensitive enough for single character change [26]) and robustness (cannot differentiate horizontal flipped images [27]).

In summary, the problems with a screenshot approach are:

- Time-of-check-time-of-use problem (TOCTOU): an attacker can show one set of UI when a screenshot is captured, and another when the user interacts.
- A validation method must be robust and sensitive at the same time.
- User input problem: how to ensure input integrity solely from the user interface.

III. DESIGN

In this section, we will illustrate the idea of our defense and go into the details of each component. Our approach is still based on screenshots, for which we aim to solve the shortcomings.

A. Assumptions

We list the assumptions in our work. VInt utilizes a standard virtualized environment with a trusted virtual machine (VM) that executes most of VInt’s code and an untrusted guest OS that owns the network stack, rendering stack and browser. Any data from the OS is untrusted by VInt and if non-authentic values are provided by the OS, it will only result in the request being deemed as non-user-intended. We make the following assumptions about the hypervisor:

- The hypervisor has the ability to intercept input events before a guest sees it. This is commonly available on recent processors with Intel VT and AMD V.
- Availability is not considered.

Fig. 4: An example VInt-enabled web page with highlights on a user’s position of focus (POF) and a submit button.

Fig. 5: An example trusted context generated by the service with page breakdown annotated for illustration purpose. The colored boxes indicate the corresponding validation method discussed in §III-D2.

from other sources for which VInt has no access and cannot guarantee the integrity and authenticity. Incorrect information shown on other sources can impact the user’s perception and behavior [29]. VInt assumes a trustworthy user that is not trying to intentionally send out requests and later claims the request to be unintended. We will describe our user behavior model in §III-E.

B. VInt Overview

We propose VInt, which ensures that outgoing network requests to service are user-intended. VInt 1) captures “what the user sees”, 2) ensures what the user sees is rendered correctly, 3) extracts the on-screen user-provided textual inputs, and finally, 4) ensures an outgoing request to the service is generated correctly from the user-intended inputs. Finally, the request sent to the service must be cryptographically signed by VInt upon 1) the successful validation of the context for the entire session, and 2) the successful comparison of the request and the extracted user-intended inputs.

1) Workflow: VInt’s main components are listed in Fig 6. VInt’s main functionality is implemented inside a secure virtual machine (VM), an untrusted browser plugin is responsible to signal the begin and the end of a VInt session and the handling of requests for validation.

VInt system begins when a VInt-enabled page has finished loading (Fig 4), for which the browser plug-in will acknowledge VInt with a rendering manifest. The rendering manifest for validating the local context. First, VInt defines a rendering manifest that contains a few client-side configurations which result in semantic-changing rendering variations when rendered by a client. A client-specific manifest is collected and securely transmitted to the service. The service will generate 1) a rendering of the web page based on the rendering manifest in a trusted environment, for which we refer to as the trusted context, and 2) a breakdown of the web page to aid the local validation. The local verification algorithm compares the local context to the trusted context using image analysis and Optical Character Recognition (OCR) to determine if they are semantically equivalent. Semantically equivalence implies the absence of context forgery attacks.

To achieve input integrity and authenticity, VInt requires the help of the human user through an assumption called “what you enter is what you wanted” (WYEIWYW). WYEIWYW requires the human user to ensure the displayed textual inputs are user-intended. This assumption allows VInt to extract on-screen textual inputs with integrity and authenticity guarantee. However, since the user can only check the on-screen textual inputs where she is focusing on, VInt must track the user’s focus. VInt develops a model that translates a user’s focus to visual indicators, which we refer to as the position of focus (POF). Example of POF includes the blinking input cursor, focus box and selection highlight. VInt extracts user inputs at the POF before the focus is lost. Together with the contextual information on the UI close to the user inputs, such as input field labels, VInt can acquire the semantic of user inputs.

Because malware can fake the entire interaction while the user is absent, VInt ensures that an actual human user is present by correlating on-screen activities to hardware IO activities. For instance, VInt requires on-screen textual inputs to appear only shortly after keyboard IO activities.

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is sent to the trusted context generator. At the same time, VInt begins collecting the local context. Two things will be sent back from the service: 1) a trusted context and 2) a breakdown of the web page. The local context is validated to have the same semantics as the trusted context using the page breakdown. Any user-provided inputs that the user entered with POFs (highlighted in Fig 4) are extracted and stored. During this time, VInt also checks for hardware IO to ensure the on-screen activities are not entirely forged by a malware. The end of a VInt session is again signaled by the browser plugin when the user clicks on a predefined submit button (highlighted in Fig 4). The generated request will be intercepted by the browser plug-in before transmission and submitted to VInt for signing. VInt will check if the request matches the captured user inputs. Upon a successful match, VInt will sign the requests with its private key for which VInt begins collecting the local context. Two things will match the captured user inputs. Upon a successful match, VInt will sign the requests with its private key for which VInt will sign the requests with its private key for which VInt’s collection pattern.

To “see what the user sees”, VInt captures screenshots of the user interaction while the user interacts with a web page with a security-sensitive web page. The screenshots are taken just before the display data is sent to the output device (sampling a VNC connection) to ensure VInt and the user agree on the context. In the rest of the paper, we refer to the series of screenshots taken with the user’s interactions on the web page as a local context.

VInt collects the local context with randomness to prevent time-of-check-time-of-use attacks. Periodic context collection is subject to temporal integrity violation attack. The attacker can expose the proper UI for a small amount of time and thus the change is unnoticeable by a human user. To solve this problem, VInt waits for a random time before consecutive context collections. This way, even if the attacker knows the presence of VInt, he cannot predict VInt’s collection pattern.

The requirements for the frequency and amount of randomness in context collection are contradictory. On one hand, today’s display frame rates have exceeded 60 frames per second (FPS), but context collection at 60 FPS introduces too much storage and processing overhead. On the other hand, VInt needs to collect as frequently as possible to detect possible integrity violations. A previous study in exposure time and perceptual memory shows that within a 500 ms exposure window, a user can only recall 50% of the exposed content. Therefore, VInt uses 500 ms as the exposure limit. Cz assumes that any tampered content can be exposed to the user for a maximum of the exposure limit, and the user’s perception will not be affected. We find that we were able to achieve a good balance of performance and security by sampling within a normal distribution around a mean of 250 ms and a standard deviation of 83 ms, we ensure that 99.73% of the time, the time between to consecutive context collections will be under 500 ms.

D. Output Integrity and Authenticity

To ensure output integrity and authenticity, different from prior works’ export-and-secure approach, VInt opts for an outsource-and-verify approach, where the rendering is entirely outsourced to the untrusted OS, and VInt only verifies the final output. Assuming a securely rendered web page (trusted context) is available for local validation, because a successful context forgery attacks must change the semantics, output integrity and authenticity are achieved if the local context has the same semantics as a trusted context. Therefore, VInt needs to determine what is the semantic-changing difference between a local context and a trusted context and ensure the absence of semantic-changing differences.

1) Semantic-changing Differences: It is difficult to construct a system that can classify whether two rendered displays will be perceived by a human to have the same semantics. Not only it is difficult for a computer program to measure a human’s subjective perception, but also current image classification algorithms are not perfect and require very large training sets to be effective. It is not clear how to get a labeled training set of semantically different images.

Therefore, VInt measures the opposite: the allowable difference between the two renderings. In benign web pages, differences can arise due to the specific display, browser, driver, or hardware used. We refer to the differences, due to client-side configurations, as rendering variations. The rendering variations in prior work are intensified by a malicious service with the use of special elements such as an HTML5 canvas, while this paper deals with benign cases.

When comparing two renderings, a naive solution is to conduct a pixel-by-pixel comparison, but this solution does not work. Due to rendering variations, the trusted context must be rendered under the exact same client-side configurations. However, the number of configurations that can affect the appearance is more than traditionally considered factors such as the monitor size, browser and version, GPU driver version, and GPU hardware type, and it is impossible to collect all of them. For instance, macOS adjusts the color and intensity based on ambient sensors and Windows ClearType has a five-step configuration dialog where each step has 2 to 6 options. We suspect that there are many other configurations. Plus, due to the proprietary nature of commercial OSes, it is impossible to determine what configurations contribute to rendering variations. These settings, although altering the screen minimally, will result in false positives in a pixel-by-pixel comparison.

We set up experiments on popular websites to evaluate the level of benign rendering variations. We chose a total of 119 top-visited websites that consist of various texts, forms, input boxes, and images. We rendered these websites in various resolutions, browsers (Chrome version 81.0.4044.138, Firefox version 76.01, Safari version 12.1.2 and Edge version 80.0.361.109), OSes (macOS 10.12.6 and Ubuntu 16.04.1) and hardware (Intel Iris Graphics 5100 and Intel HD Graphics 4000). We chose popular websites because they give an upper bound on the amount of rendering variations; we believe security-sensitive pages can be modified to have a lower level of rendering variations than the popular web sites. We observed the following typical rendering variations (with examples in Appendix C): 1) Window size affects the amount of information in the rendering, 2) OS settings, such as default font size, change the layout of the rendering, 3) Unique style. Each browser has unique default style rules. For instance, the same height in pixels may be interpreted differently in different
browsers, which means that elements may be slightly shifted on different renderings. 4) Text difference. The pixel-level appearance of text is different due to various text-sharpening techniques. 5) Color difference. Comparing images in img tags, their size and color differences are minimum: the maximum we found was 15% in HSV color space.

These rendering variation findings can be classified into three types based on how a client-side validate should handle them:

- Semantic-changing rendering variations (SCRV): benign variations such as Window Size and OS Settings that change the semantics of the page because either the page layout changes or the number of UI elements change.
- Non-semantic-changing rendering variations (NSCRV): Text and color differences do not change the semantics.
- Correctable: Unique style falls outside of typical variations, as they can be solved with modifications (CSS reset scripts) to the web page. VInt assumes that these variations are dealt with by a service on VInt-enabled pages.

It is difficult for a client-side checker to distinguish these benign variations from a context forgery attack, which also changes the semantic of the interface. In the following section, we will describe how a validation method handles both semantic-changing and non-semantic-changing variations, in order to distinguish semantic differences.

2) Validation Method: The goal of the validation is to 1) ensure the absence of SCRV but 2) allow NSCRV between the local context and a trusted context. With the idea that a remote service can aid in client-side validation, VInt proposes to use 1) a rendering manifest to account for SCRV and 2) a region-based validation method for NSCRV.

To handle SCRV, VInt constructs a rendering manifest with the client-side configurations that contribute to SCRV, such as the window size (width, height) in pixels. With this rendering manifest, a service can generate a ground truth rendering in a trusted environment (a.k.a. trusted context) so that, compared to a local context, there is no SCRV. Even though a more detailed rendering manifest eases the client-side rendering, it is a trade-off between service-side and client-side computation. While the rendering manifest is collected by an untrusted OS and cannot be trusted, we note that any crafted rendering manifest will not allow an attacker to bypass validation because it will only result in VInt validating the local context against another properly rendered context.

To handle NSCRV, VInt develops a region-based validation method for NSCRV based on image and pixel analysis. Different UI elements have different validation requirements. For instance, an attacker can tamper with a single character, which is only a few pixels difference; while a benign system may render an image with a color shift, which affects a large number of pixels. Therefore, VInt decomposes the UI elements on a context into three types: textual, graphical, input and applies different validation methods: 1) textual content is compared against the same text in the trusted context using Optical Character Recognition (OCR) 2) input content is not validated because its value is user entered (we discuss the integrity of user inputs in the next section), and 3) graphical content is validated based on the typical rendering variations we found in the previous section. Specifically, we define two renderings to be semantically different if any of the following condition is met.

- Content difference: when one rendering has more text or images than the other. For instance, an attacker can add, change or remove text to change the semantics of a paragraph.
- Color difference: for images, when every pixel of the two aligned images differs by more than 20% in HSV color space.
- Position difference: when the relative position of a UI object differs by 10% of the size of the UI object. Without position difference, a malicious attacker is free to move around the UI objects and that changes the semantics. For instance, an attacker can swap the position of “Confirm” and “Cancel” buttons and have the user trigger the request unintentionally.

The classification of UI elements into regions is done by the service and based on the desired method of validation, rather than its underlying implementation. The service is responsible for this classification which can be justified because they design the web pages. The region classification is sent to VInt together with the trusted context. We show an example in Fig 5. The page breakdown is manually annotated with dashed red lines for illustration purposes. The UI elements in black are graphical elements and elements in orange are input elements, and the rest is textual elements. The reason why the two buttons are different types is because of how they are constructed — the clear button is image-based, while the submit button is text-based.

With rendering manifest and region-based validation, the room for an attack is small. For textual regions, the attacker cannot tamper with existing texts, due to the accuracy of OCR. For graphical regions, an attacker cannot violate any of the constraints set above, which means the attacker can only shift the UI object within a small region, slightly change the color of images. We consider those as non-semantic-changing.

E. Input Integrity and Authenticity

To ensure input integrity and authenticity, VInt again opts for an outsource-and-verify approach, where it outsources the processing to the untrusted OS, and requires the aid from the human user to verify the input through an assumption called "What you enter is what you want" (WYEIWyWY). WYEIWyW requires the user to ensure that on-screen inputs are intended. This assumption is justified as human users operating on security-sensitive pages tend to be more careful in ensuring they typed the correct values by checking the displayed inputs.

However, the display of user-provided inputs is subject to temporal integrity because an attacker can tamper with the value any time after the user enters them. VInt defines temporal and spatial constraints on the validity of the user-checked inputs using user focus. The idea is that when a user has a focus on an input they enter, they can ensure the inputs are intended. Gyrus [3], which also uses on-screen inputs as user intention, requires the user to check that all inputs inside a text input field that are user-intended. This does not only require extra user effort, but it is also error-prone when the input field contains many characters, e.g. a long email in a text area. VInt only requires the user to check inputs as they are being typed.

To track user focus, VInt relies on existing visual indicators e.g. a focus box and input cursor. We refer to the visual indica-
tors as the position of focus (POF). There are two properties of POFs that make them equivalent to a user’s focus: 1) forward \(\Rightarrow\) : human users rely on POFs to know where to enter text, thus POF implies user focus and 2) backward \(\Leftarrow\) : when a human user makes edits, a functioning system must put POF at the user’s position of edit, thus user focus implies POF. These two properties give an equivalent relationship \(\Leftrightarrow\) between user focus and POF. Further, due to WYEIWW, user focus implies user-intended text. Thus, we can say that POF implies user-intended text. Therefore, VInt can track POF and only accept text edits accompanied by POF as legitimate user inputs — edits without POF can be considered non-user-intended. Currently, the type of POF used in VInt includes selection highlight, input cursor (caret) and focus box (outline).

POF is input field-dependent and applies to input fields that have the same appearance value and code value. VInt can guarantee input integrity by extracting values from the context because it relies on the direct mapping of appearance value and code value of inputs in textboxes. However, for other input fields, such as a drop-down menu, the appearance, and code value can differ (e.g. a drop-down can show value "ABC" on the screen, but the value behind is "xyz"). This gap prevents VInt, who only observes the context, from knowing the code value. However, this limitation can be overcome if VInt and the services share a scheme for the display value and code value mapping.

With the POF model defining user actions, VInt can track POF and only consider edits accompanied by POF as user-intended; edits without POF can be ignored. Therefore, VInt must 1) locate and track POF and 2) extract user-provided inputs at POF.

1) Locate and Track POF: To narrow down the possible POF styles, VInt requires all VInt-enabled services to adopt a standard design for all POFs and acknowledge, train and educate users to recognize the design. If any non-standard design shows up, the user should be alerted. Then, on the client-side, VInt performs consistency checks to ensure that 1) only the standard POFs are presented and 2) no more than one set of POFs are presented at any given time and 3) no logical errors such as one input box with a focus box but the other field has the input cursor. This prevents an attacker from showing multiple POFs and confusing the user.

Consistency checks do not enforce the absolute correctness of POFs with regard to the hardware inputs; the checks only ensure that the user and VInt agree on the shown POFs. Since POFs are maintained and rendered by the malicious system, the system can tamper with it in any way it wants; it is difficult for VInt to determine whether the system has reacted correctly with respect to the hardware inputs — doing so requires another trusted system as a reference. Therefore, VInt uses consistency checks to verify that the system has presented the POFs consistently during the user’s interaction.

2) Extract user inputs at POF: VInt develops extraction rules for input methods that can insert multi-characters at once. Many input methods can insert multiple characters at once such as copy&paste, drag&drop and multi-characters selection and deletion. VInt needs to differentiate between multi-character text entries and malicious tampering. VInt develops the following extraction rules to cope with multi-character insertion/deletion.

- **Left-side Insertion**: inputs can only be inserted on the left side of the input cursor.
- **Left-right Deletion**: inputs can be deleted from both sides of the input cursor.
- **Highlight Selection**: if multiple characters are selected (highlighted on the display), they can be deleted at the same time.

These rules restrict text changes to be near the input cursor and allow input methods to insert more than one character at a time. There is no upper bound on the number of characters inserted.

VInt will not accept input changes outside of the user’s visible area, which can happen when scrolling or input overflowing. There are two cases in which VInt has accepted the inputs before. If VInt has accepted the inputs before and that input moves out of the currently visible area, which can happen when scrolling, VInt will simply not accept changes to that input. If the user uses an input method that enters multiple characters in one shot and the added characters overflow the input field, because the overflowed text is never visible on the screen, VInt will not be able to accept its value. Therefore, VInt requires services to design textboxes large enough to hold anticipated inputs so textbox overflow never happens. This requirement has been acceptable in our experiments with transaction web pages, as fields like amount, credit card number already have a fixed length.

It is possible that the user can operate fast enough between two consecutive collects and trigger a false alarm of the extraction rule. For instance, if the user types a character then immediately moves the input cursor to the left side of it. This will trigger a right-hand insertion alarm because to the checker, the character appears on the right side of the cursor. We think this is unlikely as a recent study [34] shows that an experienced typist has a typing speed of 62 words per minute, which translates to 1.3 characters between two consecutive context collections. Another way to solve this is to relax the left-side insertion rule to a left-right insertion rule with a maximum number of 1 character of the right side of the input cursor.

Due to the fact that VInt extracts inputs from the context, an attacker is forced to leave a visual footprint in order to tamper with or forge network requests. Any abnormal behavior will be caught, depending on what is being tampered with: 1) POFs tampering will be caught by consistency checks 2) user input tampering will be ignored by VInt unless it is near the POF, and 3) input tampering near the POF will be caught and corrected by the human user.

To prevent malware from crafting an entire interaction session, VInt requires on-screen activities to follow hardware IO events. For instance, if the cursor is moving, then there must be hardware IO from the mouse; if the text is being entered, then there must be hardware IO from the keyboard. Because the hardware IO check is only to complement context validation, and the semantics of user inputs are extracted from the context, this means the hardware IO check can be coarse-grained; VInt only checks for the existence of the hardware IO when there are on-screen activities. For instance, when the user presses “a”, the user also expects “a” on the display. Because VInt extracts user inputs from the display, there is no need to interpret the semantic of the hardware IO event for the press
"a". With the help of recent hardware virtualization extension (e.g. Intel VT), the code base is as be small.

The semantics of the user inputs can be acquired from the contextual information such as form labels. In the common case, form labels are placed on the left side of the input fields. For instance, the label "Amount" on the left side of the textbox suggests that the text value is for the amount. The user inputs and input labels tuple, e.g. ("Amount", 100), allow VInt to check outgoing requests.

F. Outgoing Requests

The final outgoing request must be submitted by the local OS, and VInt requires two conditions before signing it: 1) whether the output was ever tampered with during the user interaction session and 2) whether the request was generated from user-intended inputs. The first condition ensures output integrity, authenticity and temporal integrity while the second condition ensures input integrity and authenticity are carried over to the request. When all five properties are achieved, we conclude the request to be user-intended. VInt signs any user-intended request with its private key, and services can validate the signature using the public key. Any unsigned request can be deemed as non-user-intended.

VInt assumes a format of outgoing requests. VInt assumes that the web page sends a list of input labels and input values to the service, where the user label is the form label that appears on the left side of a form input field, which VInt uses to collect user inputs. This allows VInt to perform a check on the request by checking 1) whether all collected input labels are presented in the request and 2) whether all input values are identical between VInt’s collection and the request. VInt will not sign the request if a check fails. The web page gets notified by the browser plugin when this happens.

VInt does not support more than one request at a time. However, we believe that VInt can be enhanced to support multiple concurrent requests if there is a unique identification on the user interface that VInt can extract and link to the request. This identification must be unique for all browser tabs on all browsers on the user client.

IV. IMPLEMENTATION

VInt has three parts: a trusted context generator on the service side, an untrusted browser plug-in, and a trusted checker on the client-side. To implement the checker, VInt employs a virtual machine (VM)-based isolation to separate the checker from the untrusted client OS. We implemented VInt using a Linux/Xen host running Ubuntu 16.04 and a dom-U also running Ubuntu 16.04. We note that VInt’s architecture is limited to neither the host software configuration nor the desktop environment. For instance, VInt could use a micro-hypervisor [35], [36] for a reduced footprint. It can also be ported to the Android platform with minimum changes.

A. Browser Plug-in and Rendering Manifest

We implement the browser plug-in in Chrome. The browser plug-in signals the start when a VInt-enabled page has been loaded; it signals the end when it sees a submit button has been clicked. The browser plugin communicates with the trusted checker through the network, where it sends data designated for the checker to a predefined IP address. After the page is loaded, the plug-in constructs a rendering manifest and sends it to the checker. VInt only requires the window resolution to be submitted in the rendering manifest, which specifies the height and width of the window in pixels. The window resolution accounts for both the size of the browser window and the OS default font size (when the default font size increases, the window size gets smaller).

Because the browser plug-in runs in the untrusted guest OS, its data are not trusted by VInt. The start signal cannot be fired ahead of time or delayed because VInt immediately begins validation and expects an unfilled empty page (no user inputs). The end signal cannot be fired in advance or postponed because VInt checks for the position of the cursor and hardware IO: 1) the cursor must fall on a submit button and 2) there must be a hardware click event from the mouse before the end signal. The impact of a fake rendering manifest has been discussed in §III-D.

B. Checker

The checker is implemented inside a dom0 secure virtual machine on Xen hypervisor. Due to the split driver model in Xen, guest hardware IO activities are visible to the dom0. Thus, we collect USB data simply through a usbmon and we monitor the guest network IO through tcpdump. VInt assumes that the user interface is set up through a VNC connection, thus, the checker collects the local context by sampling this connection.

Validation Method. The validation method relies on Tesseract [37] for Optical Character Recognition (OCR) and OpenCV for image analysis. User scrolling is handled by image alignment. The exact algorithm is listed in Appendix B.

Consistency Checks. VInt locates the POF using image analysis and enforces consistency checks on the focus box, input cursor and selection highlight. The appearance of POFs are listed in §III-A.

1) Performance Considerations: Difference Detection.

Due to the frequent screenshots, the difference between every two consecutive screenshots mostly occurs in a small area. Therefore, rather than re-validating the whole page, VInt limits the scope of validation to the difference between the current frame and the previous frame, which provides a significant speed-up of the content validation.

Cache. VInt relies heavily on caching to improve performance. There are currently three levels of cache: text, graphics, and frame. The text cache caches the OCR results, which saves repeated computation on recognizing the same text. The graphics cache caches the results of pixel validation; this cache is hit when only a graphic region is not changed. Finally, there is a cache for the entire frame, which has a high hit rate when the user idles. We opt for conservative caching behavior by using SHA256 digest of an image as the cache key meaning that a single pixel difference between two images will prevent them from sharing the cached result. SHA256 achieve a decent balance between low collision and performance, but if small variation should be accounted, another implementation option is to use an image hash [24].
V. LIMITATIONS

Dynamic Content. Some pages change appearances based on user inputs through JavaScript. VInt, at its current stage, does not handle any dynamic content. VInt treats the entire display as a static image for comparison with a static remote context image. It is possible to extend the checker to validate the local context against a set of allowable user interface.

Non-service-controlled content. Advertisements inside iframes are provided by third parties (e.g., advertisement providers), and the service may not know the appearance of the content. There are two concerns: 1) the third party may launch a context forgery attack using the iframe it controls, and 2) the appearance of any third-party content cannot be included in the trusted context. Therefore, VInt requires any non-service-controlled content to be removed from security sensitive pages or the service includes the expected appearances in the trusted context.

VI. EVALUATION AND DISCUSSION

A. Security Evaluation

1) Existing Attacks: We discuss how VInt defeat against user-impersonating attacks.

Request Forgery. There are two cases with request forgery depending on whether the request was forged or tampered. A forged request does not have a context associated with it, while for a tampered request, the outgoing network requests will be different from user-provided on-screen inputs, the checker will not sign the request.

Service UI Tampering. Service UI violations (Fig 7 and 1) cannot happen due to UI validation. The attacker has to either change textual or graphical elements on the display to affect the user’s perception. Those modifications will be detected by the UI validation step, and any requests generated from those contexts will not be signed.

Host UI Tampering. There are two cases when user-provided inputs are being tampered: with and without POF. In the first case, since VInt performs consistency checks, there is only one set of POF on the user interface, and since VInt requires a hardware IO, thus a user must be present, assuming the physical user enforces WYEIYWY, the user will correct any tampering. In the latter case, inputs tampered without POF will be ignored by VInt, for which the request generated from this context will differ from what VInt extracted, and VInt will not sign the request.

Temporal Integrity. First, due to the randomness in VInt’s context collection (§III-C), it is unlikely (0.27%) that any output integrity violation will be undetected for longer than 500 ms, which was the exposure limit VInt picked. If the violation is detected, then the UI validation will fail, and thus VInt will not sign the final request.

2) Adaptive Attacker: An adaptive attacker may use adversarial examples to fool the OCR into having a different understanding of the user interface than a human user. We acknowledge the existence of generic [38], [39] and OCR-specific [40]–[42] attacks, it is unknown how effective these attacks are against VInt. First of all, the field of adversarial example defenses is rapidly evolving [43], [44]; these defenses can be integrated into VInt. Secondly, OCR systems are harder to attack as a human user will alert to perceivable perturbations. Lastly, current OCR systems are different from traditional deep neural nets, it is an end-to-end neural network where any perturbation needs to cross many characters [41], which make these modifications more obvious to a human user. In conclusion, the focus of this paper is not to defend against adversarial example attacks, but these attacks have the potential to cause VInt to have a wrong understanding of the user interface.

3) Trusted Computing Base (TCB) Size: The TCB of VInt is detailed in Table II. The majority of TCB comes from two parts: 1) userspace libraries, which includes OpenCV and Tesseract and 2) the hypervisor. For the userspace libraries, we provide the following arguments and potential improvements. Firstly, we use only a small portion of the libraries; not all code in the libraries are needed for VInt. We believe that code minimization can significantly reduce the amount of code in those libraries. Secondly, these libraries are offline tools and do not communicate with the outside world. Therefore, they are hardly exploitable compared to drivers. And lastly, our libraries run in dom0, which should be protected by the hypervisor from a malicious guest. The large TCB for dom0 kernel and the hypervisor is due to our choice of hypervisor and the driver model of Xen. Rather than using Xen, VInt can be implemented with micro-hypervisors such as Bitvisor [36] and XMHF [35] to minimize the codebase.

Compared to other works, it is worth noting that VInt does not require a trusted rendering stack [4]–[6], or any external devices [5], [6]. If VInt were to be implemented using micro-hypervisors, the only additional drivers needed would be a simple network driver and a simplified USB driver for the existence of the USB hardware IO (as opposed to full USB drivers). A micro network stack such as uIP [45] contains less than 3k LOC.

B. Empirical Evaluation

We aim to answer the following questions empirically.

• Q1: What is the accuracy of VInt’s UI validation in distinguishing semantic-changing differences? (§VI-B2)

• Q2: How much overhead does VInt introduce to a network request on commercial web pages? (§VI-B3)

1) Data Composition: Ideally, end-to-end evaluation of VInt requires us to manually modify the web page source to comply with VInt’s requirements and then render the modified web page as a trusted context, and then simulate local context by creating attack variants. This method is not scalable and requires a large amount of manual effort. We want to precisely evaluate VInt’s accuracy and performance. In essence, VInt
TABLE III: The make-up of VInt’s evaluation set. SD stands for semantic difference. The number refers to the number of pairs of web page renderings with (W SD) or without (W/O SD) semantic differences.

| Configurations                  | W/O SD | W SD |
|---------------------------------|--------|------|
| Mac Chrome and Firefox (MCMF)   | 19     | 100  |
| Mac Chrome and Safari (MCS)     | 16     | 103  |
| Mac Chrome and Edge (MCE)       | 34     | 85   |
| Mac Chrome and Ubuntu Chrome (MCUC)| 35    | 84   |
| Mac Firefox and Ubuntu Firefox (MFUF)| 16    | 103  |
| Ubuntu Chrome and Firefox set 1 (UCUF1) | 16    | 103  |
| Ubuntu Chrome and Firefox set 2 (UCUF2) | 15    | 104  |
| Total                           | 164    | 669  |

TABLE IV: UI validation accuracy result. On the left is the breakdown of the number of pairs of web page renderings. On the right is the total percentage.

| Configurations | TP | TN | FP | FN | Precision | Recall | Accuracy |
|----------------|----|----|----|----|-----------|--------|----------|
| MCMF           | 100| 17 | 2  | 0  | 97.86 %   | 100 %  | 98.2 %   |
| MCMS           | 103| 13 | 3  | 0  | 97.86 %   | 100 %  | 98.2 %   |
| MCE            | 85 | 31 | 3  | 0  | 93.75 %   | 100 %  | 98.2 %   |
| MCUC           | 88 | 29 | 2  | 0  | 96.15 %   | 100 %  | 98.2 %   |
| MFUF           | 103| 13 | 3  | 0  | 97.86 %   | 100 %  | 98.2 %   |
| UCUF1          | 103| 14 | 2  | 0  | 96.15 %   | 100 %  | 98.2 %   |
| UCUF2          | 104| 15 | 0  | 0  | 100 %     | 100 %  | 100 %    |
| Total          | 686| 132| 15 | 0  | 99.47 %   | 66.67% | 98.2 %   |

otherwise, it cannot distinguish benign text shift from malicious text tampering. However, we observed that there are pages, such as Apple and Google Play Store, that never suffer from spacing issues across rendering environments. This proves our assumption that pages can be modified to reduce rendering variations and specifically, spacing issues.

- Pop-up windows, which also violates our content difference rule. A rendering with a pop-up window carries different semantics, and VInt must detect it.

Even though the number of pairs of web pages without semantic difference is low, the pairs of web pages with semantic differences simulate various types of context forgery attacks. Specifically, advertisements and page content difference simulate service UI tampering, while pop up windows simulate temporal integrity violations caught by VInt. If VInt can achieve high accuracy on this set, then we can conclude that VInt is good at detecting semantic difference while allowing non-semantic difference.

2) Q1: Validation Accuracy: In this section, we aim to figure out the accuracy of UI validation. In this experiment, we simulate a local context and a trusted context using a pair of renderings on different platforms. Because VInt requires the service to mark the regions for validation, we opt for a coarse-grained region marking scheme by treating all text regions, found by a text detector, as text regions for validation while leaving the rest as graphical regions. This coarse-grained marking scheme may not be perfect as the text detector may not give perfect results. In deployment, we envision the region marking scheme to be done by a developer on the service side. We compare the results given by the UI validation against our manual labels and show the result in Table IV. We use true positive to denote pages with semantic-changing differences and are detected by VInt. The high recall rate on the commercial website collection proofs VInt’s robustness.

The reasons for the false positives, where pages without semantic-changing difference are being flagged by VInt, are listed below (with examples provided in Appendix E)

- Foreign language on the website for language selection (six cases). VInt currently only supports English and thus OCR returns gibberish values for foreign language and thus fails text validation.
- OCR did not properly recognize text with mixed font sizes in the same line (three cases).
- Our coarse-grained web page segmentation method mistakenly treats text in images as actual text regions but OCR did not properly recognize those text (six cases).

We think these are limitations of the component tools in
VInt; they can be mitigated by restricting the page styling on the service side. For foreign languages, it is possible for a service to use an image-based (nation flags) language selector so that VInt will perform pixel comparison instead of attempting to extract text. Similarly, our OCR engine is never trained to recognize mixed font sizes, thus either the service will have to remove the style or mark text with different font sizes in separate text regions. Finally, coarse-grained region marking can be improved by each individual service for finer-grained region marking.

3) Q2: Validation Performance: We evaluate the performance of UI validation. VInt sits on the critical path between the client and the service, thus any request sent to the service is delayed until VInt’s validation finishes. Due to the difference detection method described in Section IV-B1, VInt spends the majority of its time on the first frame and is significantly faster for the subsequent frames. Therefore, we separately evaluate the two scenarios. All evaluations in this section are done on the renderings in the UCUF1 configuration on a desktop computer with a quad-core Intel i7-7700 and 16 GB of RAM and an Nvidia 1060 GPU with 6 GB of video RAM. The dom-U runs 7 logical cores and dom-0 runs 1 logical core and 1 GB of RAM.

**First Frame.** We measure the performance of VInt on the first frame of a user interaction session. VInt is an online tool, meaning that, as soon as the context collection begins, the validation also begins. The subsequent frames are not validated until the first one finishes. Therefore, we measure the average number of seconds VInt spends on the first frame of the pages in our data collection in various resolutions. The result is shown in Table V.

Overall, the performance numbers for the representative set are much lower than the numbers for the whole collection. We hypothesize that forms tend to have less number of content (text and graphical elements). To figure out why our representative set is faster, we conducted a micro-benchmark.

We profiled VInt with cProfile and found that the majority of the time is consumed by component tools such as text detection and recognition. We show the percentage by each component for all pages in our dataset in Table VI. In this experiment, we use the renderings from UCUF1 in 1024 resolution.

To improve VInt’s performance, we can improve the performance of text detection and recognition. Our choice of text detector [46] can be replaced with recent works [47]–[51] for better performance. Specifically, FOTS [50] achieves roughly 40% more FPS compared to ours, and, if adopted, we estimate an overall improvement between 18.39% and 29% . Our choice of text detector [37] can be replaced with performance-turned OCR engines [52], [53]. Also, the tools we use are a generic scene detector and OCR, but VInt only works with text on web pages which tends to be more well-formatted and structured. Therefore, we expect the performance can be further improved with tools specifically designed for the web page text.

**Subsequent Frames.** We tested VInt’s performance on subsequent frames with frame difference and cache. We created a recording, in 1920 by 1080 resolution, of the user filling out a form. We measure the time that VInt requires to validate the subsequent frames. The result is shown in Table VII.

Because of the fast validation time of the subsequent frames, it is possible for VInt to make up the time spent on validating the first frame. For simplicity, let us assume that a user spends half of the time entering inputs and half of the time idling, and VInt collects local context exactly four times a second. Then, for 1920 resolution with a mean validation time of 2.53 s (from Table V), when the length of the user interaction is longer than 5.38 seconds, then VInt will be able to completely make-up the time for the first frame. In other words, if the user session is longer than 5.38 seconds, the user will only experience a validation delay of 0.165 seconds on the 1920 resolution. We think that most user interactions are longer than this delay [54], [55]. We also think the performance overhead is negligible, as a user’s tolerable waiting time is 2 seconds [56].

VInt currently only uses a single logical core, and its performance can be improved by utilizing more cores. VInt’s operation is highly scalable, as each sample of local context can be dedicated to a single core. However, since the total amount of computation resources on the client is fixed, there is a trade-off between the amount of computation used by VInt and the amount available to the user.

**VII. RELATED WORKS**

This section discusses related works. We group related works into two categories 1) user interface (UI) attacks and defenses and 2) user intention capture.

A. User Interface Attacks and Defenses

1) Attacks: User interface (UI) attacks aim at confusing and luring the user to perform unintended actions through a deceptive UI. We note that if an OS-level attacker attempts to change the UI related to a web page to cause unintended requests to be sent out, then it is a context forgery attack. Phishing is one example. In a phishing attack, a server-side attacker aims to lure the user into providing sensitive data (e.g., usernames and passwords) to an unintended service [57]–[61]. VInt does not defend against phishing attacks, as 1) VInt assumes a client-side attacker and 2) VInt requires cooperation from the legitimate service.

**TABLE VI: Average percentage of validation time by VInt’s internal components.**

| Components          | 1024   | 1680   | 1920   | 2550   |
|---------------------|--------|--------|--------|--------|
| Text Detection       | 45.98  | 57.55  | 62.78  | 72.52  |
| Text Recognition     | 52.47  | 40.72  | 35.34  | 25.65  |
| Pixel Comparison     | 0.2    | 1.25   | 0.33   | 0.29   |
| Disk IO              | 1.06   | 0.28   | 1.35   | 1.39   |

**TABLE VII: Average number of seconds that VInt needs to validate a subsequent frame under 1920 resolution.**

| Resolution | 1024   | 1680   | 1920   | 2550   |
|------------|--------|--------|--------|--------|
| Mean       | 0.165  | 0.07   |        |        |
| STDV       | 0.116  | 0.0017 |        |        |
Another class of UI attacks is clickjacking, which is popular on Android [62], [63] and the web [7], [8]. There are several variants: 1) malicious opaque overlay: the victim is overlaid partially or entirely, while the user sees and thinks she is interacting with the web page on top, her inputs, such as mouse clicks, are hijacked and passed to the overlaid victim, triggering unintended behaviors [7], [64]. 2) transparent overlay: a transparent overlay is put on top of the user interface, capturing the user’s operations [22], [65]–[68]. 3) context hiding: an opaque overlay of the entire screen except for overlay-protected elements [63]. This variant is used to cope with overlay prevention mechanisms deployed in Android.

Clickjacking and context forgery have different attack goals. Clickjacking aims to cause unintended operations on the user client, but a context forgery attacker is interested in sending unintended requests to a service. Clickjacking can be used to launch a context forgery attacks. Secondly, in this work, we address context forgery in an OS-compromised environment, while clickjacking assumes a remote attacker with a malicious application or web page. The high privilege allows a context forgery attacker to modify the user interface at various levels including kernel drivers, which traditional clickjacking attackers cannot do.

2) Defenses: Protection against phishing has been extensively studied and is commonly implemented using blacklists [69]–[71].

There are two root causes of clickjacking: 1) illegal passing of inputs and 2) UI tampering [7]. Simply stopping apps from passing inputs [72] or acknowledging the application when user inputs were provided with an obscured flag [73] raises compatibility issues. To prevent UI tampering, some techniques analyze the application in a pre-deployment phase for malicious behavior [65], [74], [75]. On the client-side, there are techniques that 1) indicate to the client that they should not be overlaid [76]–[78], and 2) detect malicious overlays [62], [65], [79]–[81]. These client-side defenses require a policy enforcer or detector. In an OS-compromised environment, the integrity of that software may not hold.

The idea of comparing two renderings to detect tampering is not new [25], [59], [80], [82], but the difficulty is 1) robust to allowable difference and sensitive to tampering and 2) working in an OS-compromised environment.

B. User Intention Capture

The comparison of these works in terms of the properties of human-machine channel is discussed in §II-C. None of these works provides full output integrity guarantee as VInt does.

1) Heuristics-based: Binder [2] and NAB [1] leverage timing as a heuristic to guess whether an outgoing network request is user-intended. Specifically, both works state that outgoing network packets that occur shortly after user hardware IO, e.g. a keyboard press, are user-intended. However, these works do not check the content of the packets, thus an attacker can send crafted or tampered requests in the background when there are user activities. The problem is known as the “semantic gap” [83], [84]. Gyrus [3] shares a similar insight in using on-screen user-provided inputs as user-intended inputs. Gyrus requires the user to verify Gyrus’ captured inputs, which is extra user effort. VInt develops a model of the validity of user-intended inputs using visual indicators and extracts user-provided inputs as user operates, minimizing the user’s effort.

2) Confirmation: The service can send confirmations (resp. notification) of the request to the user through a secure channel, allowing the user to explicitly (resp. implicitly) confirm their intention. Confirmation is widely adopted in real life and research. For instance, a user’s operation on the web may need to be confirmed through an SMS message from the service. In academics, UTP [12] uses Intel TXT residing on the host computer as the secure channel. And similarly, ZTIC [85] uses an external device.

Confirmation 1) requires an additional trusted channel and 2) the secure channel may no longer be secure. As devices are getting more interconnected, traditionally assumed secure channels may not be secure anymore. For instance, modern OSes integrate a mobile interface that allows the user to read/write SMS messages from their desktop computer [86], [87]. If the desktop is compromised, then, the confirmation message, as shown on the desktop computer, can be altered destroying the security guarantees. VInt does not rely on a separate physical device or any additional secure channel.

3) Secure IO, Display and Execution: This set of work relies on trusted input and output for client interactions with the idea that if the user sees a securely generated display, she will interact in a way that reflects her intention. Notable systems are VButton [4], Fedelius [5] and ProtectION [6]. They all secure the user’s input, deploy embedded trusted displays for computer output, and protect the request generation. VButton is based on ARM TrustZone, while Fedelius and ProtectION rely on external hardware for secure IO. VButton implements two models, one with an embedded trusted button, and the other displays a confirmation message in a secure popup window (referred two as VB-B and VB-W, respectively, in Table I).

Not only they only provide partial integrity, they also suffer a dilemma between functionality richness and security as discussed in §II-C. In addition, these systems are architecture/hardware-dependent. VInt uses the outsource-and-verify approach, thus it does not need to secure a rendering engine; it can be implemented using a security-orient hypervisor [35], [36], [88]–[90] with a smaller TCB.

VIII. FUTURE WORK

Port VInt to Android. The idea of context verification is neither platform nor architecture-limited, VInt’s current implementation can be ported to Android. While WYEIWyW remains the same on Android, when a user types, on-screen keyboards can be validated [91] and keyboard press shade, popup, and input cursor can be used as POF for input extraction, they all satisfy the two properties of POF. In fact, the checker can be implemented in Arm TrustZone’s secure world, which provides isolation from the normal world.

To conclude, in this paper, we identified a new class of user-impersonating attack, called context forgery, that leverages the modification of user interface to trick a human user into sending out unintended network requests. Using the properties of the human-machine channel, we showed that prior intention capturing works are vulnerable to context forgery attacks. We
introduced Verified Intention (VInt) and demonstrated how it can deliver only user-intended requests to a remote service. Specifically, VInt ensures the local user interface is free from tampering by checking it against a context rendered in a trusted environment — VInt checks for the absence of semantic-changing difference. For user-intended inputs, VInt extracts the on-screen user-provided textual inputs when there is hardware IO so that a malware cannot forge on-screen activities. Our evaluation shows that VInt is accurate and efficient.
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Appendix A
Examples of Context Forgery Attacks

Fig. 7: Minimum UI Tampering: assuming Alice relies on the account number from recent recipients to retrieve Bob’s account number. An attacker can alter Bob’s account number to a different value, perhaps, Mallory’s account number, and trick Alice into believing that she is sending money to Bob, but instead she is sending it to Mallory.

Appendix B
The Exact Validation Algorithm

Algorithm 1: VInt’s Validation Method

Input: Loc: local context
Trst: trusted context
T: text positions
G: graphical elements positions
I: input positions

Output: True if Loc and Trst are semantically equivalent

1 LocTextPos = TextDetect(Loc);
2 TextPosCheck(LocTextPos, T);
3 for every text position TextPos in T do
4 LocText = TextRecognition(TextPos on Loc);
5 TrstText = TextRecognition(TextPos on Trst);
6 ValidateText(LocText, TrstText);
7 for every input position InputPos in I do
8 POFPos = POFDetection(InputPos on Loc);
9 LocInput = TextRecognition(InputPos on Loc);
10 ValidateInputs(LocInput, POFPos, HistoricalInputs);
11 Labels = ExtractLables(InputPos on Loc);
12 StoreInputs(Labels, LocInput, HistoricalInputs);
13 for every graphical element position GrphcPos in G do
14 ValidateGraphics(GrphcPos on Loc, GrphcPos on Trst);

The validation algorithm is listed in Algorithm 1. The purpose of line 1 and 2 is to ensure the local context has the exact number of text as the trusted context. TextDetect uses the EAST text detector [46], and for which the result is compared with breakdown from the service. The breakdown consists of a list of text positions (T) encoded in the format of (x, y, w, h), where (x, y) represents the top, left position of the box surrounding the text and w and h represent the width and height of the box.

The loop at line 3 iterates over each text boxes and invokes Optical Character Recognition (OCR) engine to recognize the text. This recognition is done twice, once on the local context and once on the trusted context. This design choice is made to simplify the workflow. One alternative is to have the service send text along with the position information. TextRecognition is configured to 1) recognize English characters only 2) uses a dictionary of common English words to improve accuracy. It also attempts to optimize the input image before recognition. Optimization includes

- Binarization: text regions are binarized into black text on a white background.
- Scaling: binarized text regions are enlarged for better OCR accuracy [92].
- Stroke sharpening: strokes in text regions are sharpened.
- Alignment: local image is aligned to the trusted image to handle scrolling.

Function ValidateText compares extracted text from OCR. It accounts for the possible mistakes using the length of the text and a history of prior recognized values. When comparing two texts, VInt attempts to do a string comparison when the confidence returned by the OCR engine is high (≥ 70), otherwise, VInt falls back to a basic pixel-level comparison.

The loop at line 7 iterates over each input box, attempts to see if it is under a user’s focus and invokes OCR engine to extract inputs. Only inputs with a user’s focus is allowed to change from previous extracted values. Function ValidateInputs performs 1) finds inputs modifications based on historical inputs and 2) determines whether the inputs modifications are at POF. Any input modifications not at POF will result in failed validation. Finally, input labels are extracted and stored together with inputs in historical inputs used for future frames.

Similar to text validation, the loop at line 13 validates graphical elements. The exact validation method includes

- Alignment: the graphical elements on Loc and Trst are aligned.
- Color difference: color differences between the graphical regions are calculated in HSV color space.
- Color validation: the validation checks for the color difference at pixel level with a threshold of 15% for hue, saturation and brightness while accounting for value wrap around such as hue value 0 and hue value 359. Noisy under 1/70 of the width and height of the input images are removed. This threshold is chosen by experiments.

The algorithm for the subsequent frames is similar to Algo 1 with the addition of caches mentioned in §IV, and an additional function DifferenceDetection that finds the area of difference between two subsequent frames of the local context.
APPENDIX C
EXAMPLES OF RENDERING VARIATIONS

Examples of the browser-unique styles can be found at https://github.com/sw4/revert.css.

Fig. 8: Resolution. Rendering of quora.com in 1024 * 768 resolution (left) and in 2560 * 1440 resolution (right). The amount of information in the background visible to the user differs in the two renderings, and thus the semantic of the rendering differs.

Fig. 9: Pixel-level Difference of Text. The same text is rendered in different browsers. We see that the text height, width, brightness, space to the next character and color all vary in the pixel level.

APPENDIX D
EXAMPLES OF SEMANTIC DIFFERENT RENDERINGS

We show examples of the semantic-changing difference between two renderings of the same website. All renderings are from our evaluation collection.

Fig. 10: Advertisements. Rendering of Allrecipes.com on Mac Firefox (left) and Mac Safari (right). The advertisement on the top of the page shows differently in two renderings.

Fig. 11: Different web content. Rendering of Yellowpages.com on Mac Firefox Mac Firefox (left) and Mac Safari (right). The background image shows differently in two renderings.

Fig. 12: Spacing. Rendering of craigslist.org on Mac Firefox Mac Firefox (left) and Mac Safari (right). The spacing of text is not consistent on two renderings.

Fig. 13: Pop up Window. Rendering of forbes.com on Mac Firefox Mac Firefox (left) and Mac Safari (right). The rendering on the left has an additional pop-up window which is not presented in the rendering on the right.

APPENDIX E
EXAMPLES OF FAILED VALIDATION

We show example causes of false positives in VInt’s validation.

Fig. 14: A language selection bar on facebook.com where VInt failed to recognize the text.

Fig. 15: Mixed font sizes on xfinity.com where VInt fails to recognize the text.
Fig. 16: An example of failed validation due to the coarse-grained region marking on play.google.com. The text "The invisible man" in the image is being mis-detected resulting in failed recognition and comparison.