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Verifiable Access Control for Augmented Reality Localization and Mapping

Abstract: Localization and mapping is a key technology for bridging the virtual and physical worlds in augmented reality (AR). Localization and mapping works by creating and querying maps made of anchor points that enable the overlay of these two worlds. As a result, information about the physical world is captured in the map and naturally gives rise to concerns around who can map physical spaces as well as who can access or modify the virtual ones. This paper discusses how we can provide access controls over virtual maps as a basic building block to enhance security and privacy of AR systems. In particular, we propose VACMaps: an access control system for localization and mapping using formal methods. VACMaps defines a domain-specific language that enables users to specify access control policies for virtual spaces. Access requests to virtual spaces are then evaluated against relevant policies in a way that preserves confidentiality and integrity of virtual spaces owned by the users. The precise semantics of the policies are defined by SMT formulas, which allow VACMaps to reason about properties of access policies automatically. An evaluation of VACMaps is provided using an AR testbed of a single-family home. We show that VACMaps is scalable in that it can run at practical speeds and that it can also reason about access control policies automatically to detect potential policy misconfigurations.

Keywords: access control, privacy, augmented reality, virtual reality, security, formal methods, SMT, localization and mapping

1 Introduction

Augmented reality (AR) is rapidly emerging as the next generation of disruptive technology. Like the mobile computing revolution, AR is similarly poised to change how the physical and digital world connect and interact. It provides immense opportunity for assisting and improving how we interact with the physical world by precisely overlaying the right amount of relevant information from the virtual one. Augmented reality promises to provide a wide range of applications from social teleportation [1, 2], e-commerce [3, 4], navigation [5], and contextualized artificial intelligence [6, 7].

There are countless exciting use cases for AR but all are built upon localization and mapping. Localization and mapping is responsible for determining where a user is in physical space and aligning it with the virtual world. Mapping is the process of sampling (physical) data to build new maps or update existing ones. These maps are the backbone of AR systems that bridge the physical and virtual divide. A commonly used form of a vision-based virtual map are 3D point clouds, which are composed of points in 3D space and their associated visual feature descriptors that describe the appearance of each point location (Figure 2). This representation contains the information necessary to associate a point in physical space with one in the virtual world.

Once a virtual map equivalent to the physical environment has been constructed, users interact with the map to localize into the environment. Localization is the process of querying existing maps using sensor inputs to determine where a user is in the environment. This information is used to resolve the relative locations of virtual and physical assets, enabling a precise overlay of the virtual world on top of the physical one. For instance, suppose we want to place a virtual sticky note on a physical refrigerator (assuming the physical space has been mapped). To render the virtual sticky note in

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the right spot the AR system needs the following information: (1) the physical location of the refrigerator, (2) the virtual location of the sticky note, (3) the location of the user in both physical and virtual space, and (4) the relative distance between the note, refrigerator, and user in both the physical and virtual world. Localization and mapping provides all this information by aligning the virtual world to the physical one.

While the virtual AR world has remarkable likeness to the physical world, there are important differences with respect to accessing spaces, which now depend on access to digital maps rather than just physical locations. This gives rise to the map access problem in AR. Specifically, unlike the physical world where restricting access is intuitive and solutions are readily available (e.g., locks and physical barriers), new systems and mechanisms are needed for controlling access to virtual spaces for AR. Access control systems should uphold and enforce notions of permission for map modifications, analogous to the physical world. Imagine two competing coffee shops. One shop should not be able to place advertisements for their shop in the line of the other, nor should it be able to artificially obstruct/close the entryways in the virtual world. More questions arise around who, when, and where a map can be used for localization. For example, if a map exists of a house, how does one enforce who can interact with which parts and when? Without restrictions, these digital spaces are ripe to become overrun with unwanted behavior.

In this paper we propose and develop Verifiable Access Controlled Maps (i.e., VACMaps) to address the emerging challenges of access control in AR. VACMaps is an access control system that uses formal methods to implement a wide range of configurable access control policies over maps, specifically targeting mapping and localization use cases. It also maintains a hierarchy of spaces enabling efficient look-up of relevant spaces and policies. We develop a new domain-specific language, named VMAC Lang (Virtual Map Access Control Language) to specify access control policies. The language enables the owner of a space to detail precisely who should have write (i.e., mapping) and read (i.e., localization) access to a map and under what conditions (e.g., the time of day and a user’s current location). The semantics of this language is given by a set of rules that translate the human-readable policies to logical formulas. Once VACMaps receives an access request, it efficiently collects relevant spaces and their corresponding access policies, and then evaluate the access request against the logical formula representation of the policies. Thanks to the logical formula representation of policies, VACMaps is able to formally prove claims such as “an unauthorized user will not have access to this space”, thereby protecting the victim’s private map contents.

VACMaps can verify access claims to map data given a set of access policies but there is still possibility for users to unintentionally misconfigure the access policies themselves (e.g., overly permissive access, etc.). While VACMaps would not be able to figure out the user’s real intent, it does provide a way to detect and audit potential misconfigurations. This is only possible because of the formula representation of policies that VACMaps maintains. We can then craft queries questioning VACMaps “who has access to this room?” or “is there a space in this house that no one has access to?” or “would this new policy have any effect at all?” Answers to these queries might be useful for users in order for them to author policies in a more informed manner.

This paper makes the following contributions:
- We propose VACMaps: the first system that implements access control for modern AR localization and mapping using formal methods.
- We develop VMAC Lang: a domain-specific language for access policies whose semantics are defined by the SMT encodings.
- We evaluate VACMaps and show that it can run in near real-time and can scale to large numbers of spaces and access policies.
- We demonstrate how VACMaps can be used to audit access rights and detect possible policy misconfigurations.

2 Background and Motivation

This section provides background on localization and mapping and motivates the need for map access control.

2.1 Background: Maps, Mapping, and Localization

Localization and mapping is a two part process as shown in Figure 1. Mapping is the process of creating a 3D model, usually in the form of 3D point clouds, of a physical space through computer vision algorithms, such as Simultaneous Localization and Mapping (SLAM) [8-10] or Structure-from-Motion (SfM) [11-13]. The mapping process typically takes an image from the AR device as input and generates a visual feature descriptor for each interest point detected in the image. Each interest point
is also associated with a location in physical 3D space (i.e., x, y, and z coordinates). These map points are then combined to create maps—the core data structure used to represent the physical world in machine perception algorithms. The mapping process effectively provides a binding between locations in a physical space and the digital copy for AR, which is encoded in the map. We refer to this digital copy of physical space encoded in map data as virtual spaces. Each new map then is merged into the map database on the server where GPS data is used to provide a coarse grained estimate for roughly where to align and merge the new map with.

Localization is responsible for using map data and obtaining a high-precision estimate of where a user is in both the physical and virtual world. Localization provides the 6 degree-of-freedom (DoF) pose of the user’s device by querying an existing map. This is usually achieved by registering a device’s input video stream against the map (3D model) of the physical space; additional signals, such as GPS, are also used to get a coarse-grained position estimate in the world to reduce the search space. Specifically, localization uses a set of visual descriptors extracted from user device’s input video stream and matches them against the descriptors that are associated with each 3D point in the map. Without a coarse grained GPS estimate, this matching step would search significantly larger portions of the database to get high quality matches for localization. Once the correspondences have been established, the pose is computed via a PnP algorithm. In this work, we assume that localization and mapping are performed on the server. In this scenario, the user sends visual information (e.g., visual descriptors) for localization, the server performs localization and then sends the 6-DoF pose back to the user.

2.2 Access Control Considerations for Virtual Spaces

We define a virtual space to be all map data associated with a physical space, and a private space to be a space with certain access restrictions. The focus of our work is to protect private virtual spaces against unauthorized access and tampering from adversaries. We assume users will configure access control policies over the spaces they own to protect them from unauthorized access by other users, and that these policies are provided as input to VACMaps.

In the physical world, private physical spaces are often associated with an owner or manager who poses access restrictions on other users. We expect virtual space to have similar concepts of access control and ownership but without some of the physical limitations. Unlike in the physical world, in AR users can move across vir-
tual spaces and establish digital presence as they interact with AR services. If an unwanted user establishes digital presence in virtual spaces, it raises confidentiality and integrity concerns. Examples of harm caused by unwanted access to maps via AR systems includes spying (confidentiality concerns) and vandalism (integrity concerns).

Confidentiality There are two potential concerns with confidentiality in AR maps: accessing raw map data and performing unauthorized localization.

First, map data captures information about object structure that can be used to infer what is around the user and general information about the surrounding environment [20–22]. To illustrate this concern more concretely, Figure 2 shows a point cloud visualization of the map for a canonical single-family home. In this visualization, an observer can infer details about the house layout [23, 24] and different objects [20] using existing computer vision algorithms. Prior work [25–28] has shown point clouds are not entirely secure and that point cloud data from a stolen map can be reversed to reproduce a surprisingly good visual reconstruction of the environment. If accessed by an unauthorized adversary, the map data can leak confidential information about what objects a user has or is in the surrounding environment.

Second, the ability to localize into an unauthorized virtual space using a map raises additional confidentiality concerns. Once the adversary has localized to a private space, they have access to a rich rendering of the setting. This could, for example, enable passive spying on objects in the space, e.g., a computer screen, without being physical present similar to existing spyware. Strong read access control over maps can rule out both of these cases.

Vandalism and Integrity Unauthorized modification of map data for private virtual spaces is a concern for similar reasons: tampering, adding, or deleting AR objects compromises a virtual space’s integrity. When mapping or updating a physical space, it is necessary to prevent unauthorized adversaries from degrading integrity by deleting or modifying it. Prior work has shown that degrading the integrity of point cloud models or maps can negatively impact the accuracy of downstream tasks or inject backdoor triggers [29–31]. Such attacks are loosely the virtual analog of an adversary stealing objects (deleting map data) from or posting/placing items (tampering/adding map data) in one’s physical space, respectively. Deleting or spamming map data directly degrades the quality of many AR services that rely on map integrity.

Adversaries may also attempt to modify or delete the map data of a victim. For instance, a shop may attempt to override or modify the map of a competitor to gain a commercial advantage by degrading map integrity. In a personal setting, without proper map write access control, AR users would be vulnerable to adversaries spontaneously adding objectionable content in their spaces, which may not be easy to delete without proper permissions.
3 Threat Model and System Goals

This section defines the system assumptions, adversary model, and objectives of VACMaps.

3.1 System Definition

We define our system as having two primary entities: AR device users (clients) and the service provider (server or cloud). We assume each user in this system owns an ego-centric (i.e., head-mounted) AR device that is responsible for collecting the visual information required for conducting server-based localization and mapping. These user devices interface with a cloud service provider that updates the virtual map of the world. The service provider is assumed to be honest, since it is incentivized to maintain accurate and up-to-date map data and localization estimates for users; inaccurate localization estimates or stale map data would degrade the quality of AR experiences that rely on the integrity of the map.

The primary data asset in our system is map data, which consists of 3D point locations and their associated feature descriptors. In server-based localization and mapping, the virtual map of the world is stored on the service provider as it is impractical to store all of it on any individual device; we assume that existing network security protocols and best practices ensure the channel between the device and the service provider is secure. During mapping, when a user moves through an unmapped space, the user device will generate map data and upload it to the service provider. The service provider will then attempt to merge that data into the existing map as long the user has correct permissions to write data for that physical space. If a user tries to localize into a mapped space, they will request read access to the relevant map data. The service provider is assumed to be honest, since it is incentivized to maintain accurate and up-to-date map data and localization estimates for users; inaccurate localization estimates or stale map data would degrade the quality of AR experiences that rely on the integrity of the map.

3.2 Adversary Model

We assume that a subset of AR device users will behave maliciously and either attempt to perform unauthorized map accesses to either read private data or modify/delete points of other users. A malicious adversary is able to manipulate the visual information and GPS data that is captured on the AR device before it is uploaded to the service provider. Falsifying GPS data enables an adversary to potentially trick the localization and mapping system into serving maps to localize into areas a user may not physically be present. Falsifying visual information allows an adversary to directly fabricate feature points and hence map data that can be combined with GPS spoofing to attempt to write invalid map data. However, an adversary need to model precisely the visual information as if the adversary is physically present in an environment to trick the mapping and localization system, which comes at a high cost. Therefore, we assume that an adversary is able to spoof GPS data but not visual information. Finally, we assume that malicious devices are not able to further compromise other devices in the systems, including the datacenter service provider, and that the adversary is not able to fake their identity.

3.3 System Objectives

The key objective of our system is to protect user map data of their private spaces from unauthorized access by adversaries; we define unauthorized access as any read, modification, or write request that is prohibited by a set of access control policies (see section 4). We assume that there are policies defined over physical spaces that govern the mapping, sharing, and modification of map data over these spaces which the system must comply with.

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1 We assume that the malicious user is from the public and is not mentioned in any allow policy for the map, therefore does not have permission to access the maps under any condition.
Formal methods study techniques for specification and verification. Specification involves defining a system or process and its desired properties using a mathematically defined syntax and semantics. Verification on the other hand is a technique that proves that the system or process satisfies certain properties. Formal methods are often used to prove the correctness of safety-critical systems, e.g., a flight collision avoidance system or systems that are much too complicated to verify by hand (e.g., a modern compiler toolchain).

Formal method starts by representing a system (e.g., a computer program) as formulas in Boolean logic and defines a Boolean satisfiability problem that encodes the property we wish to verify (e.g., reachability, liveness, or correctness). The Boolean satisfiability solver (SAT solver) then tries to decide whether the Boolean constraints combined with logical connectives can be made true by choosing true or false values for each variable. Depending on whether the answer is true or false, this information can be used to make claims about the system.

Boolean logic itself is often not expressive enough to encode problem that requires domain knowledge. As a result, the Boolean SAT problem is often augmented to involve predicates on integers, reals, and data structure in addition to Booleans using satisfiability modulo theory (SMT). As an example, one might ask whether there exist integers \( x, y, z \) such that \( x > 2y \land y > z \land (2z < x) \) is true. The meaning of predicates like \( x > 2y \), i.e., given symbols \( x, y \) decide if \( x > 2y \) should be true or false, is provided by the theory of linear integer arithmetic which defines the semantics of integer math. For the previous query, the solver would verify that the formula is unsatisfiable for any values of \( x, y, \) and \( z \). Other theories include theory of uninterpreted functions, theory of strings, etc. In this work, we focus on formulas within theory of linear real arithmetic with equality for which there exists efficient decision procedures.

The underlying SAT problem itself is a well-known NP-Complete problem; however, modern solvers implement sophisticated heuristics that exploit the power of modern processors and the structure of formulas to explore the search space very efficiently. As a result, modern SMT solvers like CVC, Yices, and Z3 can often handle formulas with hundreds of thousands of variables in a reasonable amount of time.

This also means SMT solvers are fast enough to support practical sized problems in areas such as program verification and testing, compiler optimization correctness, interactive theorem proving, and program synthesis. Problems in specific application domains are translated into SMT formulas such that the satisfiability of the formulas implies that certain properties must hold. For example, we can over-approximate the states that a program could run into, i.e., maintain a set of states that is guaranteed to be a super set
of the actual reachable states. Then we might encode the event that a particular error state is within this set of reachable states as an SMT formula so that if the formula is unsatisfiable then the program is guaranteed to never run into that error; and if the formula is satisfiable we could obtain from the SMT solver a concrete example of an initial configuration of the program that may run into that error (since we maintain an over-approximation of reachable states rather than the exact set of reachable states).

In our work, we describe the semantics of access policies formally using SMT formulas. Properties of the access policy semantics imply the correctness of the access control system given any combination of access policies and access requests. We will also encode certain claims about access policies as queries to SMT solvers. By examining the SMT solver output, we can then detect possible policies misconfigurations and report it to the users.

4.2 VACMaps Architecture Overview

Figure 3 depicts the VACMaps system. VACMaps provides access control for localization and mapping in the client-server setting. We assume that users have AR devices with cameras that capture visual observations of the physical world that are converted to map points. We further assume the user has defined access policies over the physical spaces they own/control and the virtual maps they create. Together, the observed map points and access policies serve as the input to VACMaps.

On the server side, localization and mapping services compute the user’s exact current location and map point coordinates using input from the user’s device. Notice that GPS, WiFi, and other measurements that provide the approximation location are not directly used to decide the user’s location but only as an aid to the localization and mapping services. The server also checks if the user’s observations match the database to ensure that the user is not spoofing its location. Additionally, the server maintains a database of access policies and the mapping between policies and spaces. These policies are either generic or user-defined. The policy database extracts the list of relevant policies needed to determine the user’s access rights. These policies are organized in a spatial hierarchy to make identifying relevant policies efficient (see subsection 4.4). VACMaps takes the relevant access policies, and the calculated exact location of the user to formulates a SMT problem. The problem is finally presented to the formal verification engine to verify whether the map access request should be granted or denied (see subsection 4.5).

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3 We assume that in practice there will be a separate system that manages the ownership of spaces which is able to decide who is allowed to modify existing policies.

4 Default policy configurations that are not user-specific (e.g., deny access to all private spaces by default).
Map access requests are modeled as read, write, and localize in VACMaps. If the user has read access, a virtual map is visible. If the user has write access, the 3D feature points that the user observed can be used to update the known map or create (write) a new one, which is stored on the server. If the user has localize access, the AR device could show the user’s relative location with respect to the known map.

For instance, we might want to deny all access requests to private spaces such as restrooms (line 20–25 in Fig. 4b). The action field lists the access events granted or denied by this policy and can be one of three types: read – request map points for the space; write – update the map of the space; localize – determine the user’s location in this space.

Space specifies the set of spaces that a policy applies to. VMAC Lang allows policy designers to specify access to spaces as (Boolean) logical expressions. For example, one can say a policy grants access to “the first floor of the house except the bathroom; and the living room on the second floor” or “third floor of the office building and the lobby”. In VACMaps, we allow user (U) access to some space (S) if and only if there exists an allowing policy (P) that grants U access to S and that there is no denying policy that prevents P from accessing S. In other words, deny policies will always override allow policies in VACMaps if there is a conflict. We assume a space has deny access rights by default.

The condition field is an optional qualifier that defines conditions under which the policy takes effect. We typically use conditions to determine access based on a user’s current location and time of the day. For example, you might allow your friends to map your house only when they are in the house; similarly, a museum might only allow visitors to localize into its exhibition spaces only during business hours.

4.4 Access Control and Spatial Hierarchy

It is natural for us to think about access rights to objects hierarchically. For example, when declaring a folder as read-only one expects the files inside also become read-only. Similarly, users might want to set certain policies on their entire house and expect the rooms inside to automatically “inherit” some of the policies. Defining policies in a way that is coherent with respect to the natural hierarchy of spaces also relieves users’ burden to define unique policies for each individual space they control. Organizing policies according to the hierarchy of spaces makes the VACMaps system more efficient. For example, fetching relevant policies from the policy database based on the user’s current location would be easier to implement given that we store the policies according to the hierarchy of spaces.

We formalize the idea of an access control system that respects spatial hierarchy as follows. We assume that if space a and space b has a non-empty intersection, then either a is contained in b or b is contained in a. We then construct a graph $G = (V, E)$ such that

\[
\langle \text{policy} \rangle ::= (\langle \text{name} \rangle, \langle \text{effect} \rangle, \langle \text{principal} \rangle?, \langle \text{action} \rangle?, \langle \text{space} \rangle, \langle \text{condition} \rangle?)
\]

\[
\langle \text{name} \rangle ::= \langle \text{Name} \rangle \langle \text{string} \rangle
\]

\[
\langle \text{effect} \rangle ::= \langle \text{allow} \rangle | \langle \text{deny} \rangle
\]

\[
\langle \text{principal} \rangle ::= \langle \text{Principal} \rangle \langle \text{string} \rangle
\]

\[
\langle \text{action} \rangle ::= \langle \text{read} \rangle | \langle \text{write} \rangle | \langle \text{localize} \rangle
\]

\[
\langle \text{space} \rangle ::= \langle \text{Space} \rangle \langle \text{space-expr} \rangle
\]

\[
\langle \text{space-expr} \rangle ::= \langle \text{space-id} \rangle \langle \text{~} \rangle \langle \text{space-expr} \rangle \lor \langle \text{space-expr} \rangle \land \langle \text{space-expr} \rangle
\]

\[
\langle \text{condition} \rangle ::= \langle \text{Condition} \rangle \langle \text{cond-expr} \rangle
\]

\[
\langle \text{cond-expr} \rangle ::= \langle \text{atom} \rangle | \langle \text{cond-expr} \rangle \lor \langle \text{cond-expr} \rangle \land \langle \text{cond-expr} \rangle \lor \langle \text{cond-expr} \rangle \land
\]

\[
\langle \text{atom} \rangle ::= \langle \text{TODAfter} \rangle \langle \text{time} \rangle | \langle \text{TODBefore} \rangle \langle \text{time} \rangle \langle \text{whenInside} \rangle \langle \text{space-id} \rangle
\]

Fig. 4. Syntax for the policy language. Here a policy is an ordered tuple of fields, and “?” denotes an optional field. If an optional field is missing, then the policy applies universally regardless of the value of that field. For example, a policy without a “principal” statement applies to all principals.

4.3 VMAC Lang: A Domain-Specific Language for Access Policies

VACMaps develops a domain-specific language (DSL), named VMAC Lang, for access control policies that defines access rights over virtual maps. Figure 4 shows the abstract syntax for the VACMaps policy DSL.

In VMAC Lang, a policy contains one or more statements. Each statement has a name, which we use to refer to the policy when changing or deleting policies. Statements have effects that declare whether this policy is granting or denying access. A statement also contains a principal $P$ that indicates the name or ID of the user that the policy applies to. The principal in a statement is optional; omitting the principal allows one to specify a policy that applies to all users. For instance, we might want to deny all access requests to private spaces such as restrooms (line 20–25 in Fig. 4b). The action field lists the access events granted or denied by this policy and can be one of three types: read – request map points for the space; write – update the map of the space; localize – determine the user’s location in this space.
the node set $V$ corresponds to the set of spaces, and an edge $(u, v) \in E$ if and only if space $v$ is contained in space $u$. Since any space $u$ can have at most one parent, $G$ is a forest. We say an access control system is said to be coherent with respect to spatial hierarchy $G$ if a policy defined for space $S$ is also enforced by the system on space $T$ if $T$ is a descendant of $S$ in forest $G$. VACMaps is a system that is coherent with respect to spatial hierarchies.

Figure 5a gives a visualization of the hierarchy of rooms of a canonical single family home. For example, the policies set on “house” will be enforced on all floors and all rooms that are descendants of the “house” node in the graph; policies set on “Master suite” will also be enforced on “Master bedroom” and “Master bathroom” since these spaces are contained inside “Master suite”. One could imagine that the management of an office building could implement a similar hierarchy for different floors that belong to different companies that have offices in the building.

Having a hierarchical structure of spaces also makes access auditing process more intuitive for users. Users and policy experts can look at the hierarchy diagram and make queries like “who has access to this particular space” and “visualize spaces that this user access” and make queries like “who has access to this particular space” and “visualize spaces that this user access”.

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For all these spaces, we then perform a substitution and cache the result against their access control expectations and/or social norms. We will introduce more features of VACMaps that facilitates policy auditing in subsection 4.5.

### 4.5 Processing Access Requests and Reasoning about Policies

We now describe how VACMaps handles access requests and caches them to improve performance. The server maintains a mapping from spatial identifiers to policy names that, given a space $S$, returns all allow and deny policies that refer to $S$ in the space-expr. Given a new access request against map point $p$, VACMaps first finds all spaces $S_1 \subseteq S_2 \subseteq \ldots \subseteq S_n$ in the spatial hierarchy that contain the map point $p$. VACMaps then translates all applicable policies to spaces $S_1, \ldots, S_n$ into an SMT formula $F$ and combines them. Policies are translated to SMT formulas in a lazy manner, i.e., they are only translated into SMT formulas when there is an incoming access request that involves space (or subspace) to which this policy may apply. The access request is then evaluated against $F$ resulting in an allow or deny decision.

To improve systems efficiency, VACMaps also maintains an LRU cache for access permissions. The data for the cache is a tuple consisting of identifier for the smallest enclosing space $S_1$ for point $p$, as well as current time of day and other contextual information in the access request (with the exception of the map point coordinates) and the access decision. Once VACMaps processed access request for point $p$, other access requests against map points in space $S_1$ with the same contextual information will be served using the cache.

Figure 5c shows how VACMaps translates VAC Lang policies to an SMT formula. First, we discuss the translation for an allow policy. The formula translation of an allow policy is done by building a conjunction of the translation of each of its statements, except for the effect statement. To translate the principal statement, we declare a string-typed variable $s_{principal}$ and we translate principal: “Alice” into an equality between the string-typed variable and a string literal: $s_{principal} = “Alice”$. The action statement is translated similarly. Next, we translate the space statement. We declare real-typed variables $x, y, z$ representing the coordinate of an incoming map point. To translate the atomic expression, which consists of simply a space identifier, we first look up the boundaries of the space. VACMaps assumes all spaces are axis-aligned bounding boxes, so the boundaries can be represented as a tuple $(l_x, r_x, l_y, r_y, l_z, r_z)$. The atomic expression then becomes $l_z \leq x \leq r_x \land l_y \leq y \leq r_y \land l_z \leq z \leq r_z$. This can naturally be lifted into a translation of an arbitrary space statement. For the condition statement, we also only need to specify how we translate the atoms. The $\text{WhenInside}$ atom could be translated in a way similar to space expressions provided that we define real-typed variables $u_x, u_y, u_z$ representing the user’s approximate location where the access request is generated. We translate the $\text{TODBefore}$ and $\text{TODAfter}$ atoms by introducing an integer-typed variable $t$ and translate an condition that encodes “after 9 pm and before 1 am” into formula $(2100 \leq t \leq 2400) \lor (0000 \leq t \leq 0100)$. To translate a deny policy, we simply take the negation of the conjunction of the translation for its statements. We give an example of a policy in Figure 5b and its SMT formula encoding in Figure 5c.

An access request $\langle p_{\text{principal}}, v_{\text{action}}, x, y, z, u_x, u_y, u_z, t \rangle$ is a tuple that contains the name of the principal making the request, the action the principal wants to perform, the coordinate of a map point $(p_x, p_y, p_z)$ in 3D space, the location of the user $(l_x, l_y, l_z)$, and current time of day $t$. To evaluate an access request, we find all spaces that contain the map point being queried and obtain a formula $F$ encoding the combined policy for all these spaces. We then perform a substitution...
We implement VACMaps in Python using textX to implement and parse our access control policy DSL. We use intervaltree to define and maintain the spatial hierarchy relationship of spaces; we also use Z3 (z3-solver) as our solver backend. All experiments were run on a MacBook Pro 2019 with a 2.4 GHz 8-Core Intel Core i9 CPU and 32 GB RAM.

To our knowledge, there is no standardized benchmark for evaluating access policies for localization and mapping or general AR/VR applications. We thus use a synthetically generated dataset for a single family house (Figure 6) that captures common scenarios that a user would encounter when they interact with an AR device at home.

The house has two stories and contains a set of rooms shown in Figure 5a. We obtain the 3D segmentation and the name of the rooms (Figure 6d) using the ground truth floor plans used to construct the house. In practice, this can be obtained using techniques like PlaneRCNN [44]. The dataset also provides a video sequence of a tour or walk through (Figure 6c) of all the rooms in the house to simulate what the camera attached to the user’s AR device would capture. This effectively generates a sequence of accesses to the map which VACMaps validates with respect to access policies.

The localization and mapping pipeline takes in as input the simulated video sequence. For each frame in the video sequence, the pipeline returns a list of feature points (both their 2D coordinates in the image and their 3D coordinates in space) that are used to decide the user’s location or update the map database. The pipeline also returns the user’s estimated location for each frame.

We assume that users send access requests to the access control system to request access rights to map points for each frame of the simulated video. An access request simply contains the user’s ID, all the feature points that the user observes at this time instant, the user’s current location, and other metadata the AR device generates (such as the timestamp) that are useful in deciding access rights.

Access policies for rooms in the house are hand-written (unless otherwise specified) to verify the correctness and evaluate the performance of VACMaps. We will discuss how we create the policies in the following subsections.

5.2 Basic Access Control Scenario Evaluation

We first evaluate the basic utility and functionality of VACMaps for canonical use case scenarios. Each of these basic scenarios that a user may encounter is briefly described in Table 1. We implement all these scenarios by crafting a set of access control policies over the rooms and using a subset of the frames in the tour that reflect the test scenario. We then inspect that the access request decision (i.e., allow/deny) that VACMaps makes is consistent with the expected result. We use these scenarios to validate the basic functionality of VACMaps as an access control system.

The results for several of these scenarios is shown in Figure 7 where RGB points denote points that the user is granted access to while red Xs denote points to which a user is denied access. Figure 7b illustrates the the scenario of shared private spaces where a user is looking into the bathroom. When a user tries to access these map points VACMaps denies access to all map points in the bathroom as indicated by the red map point annotations in the diagram. In Figure 7d the user is located in a different user’s private bedroom; similar to the previous bathroom scenario, VACMaps again denies access to these map points because the user is not authorized to view or use them. On the other hand, if the user is located in their own private space VACMaps appropriately allows the user access to the map (Figure 7h).

Finally, Figure 7f illustrates the case where there is a bystander space which may be private but is next to a common area space which is not. In this case, both the bystander space and common space are within the
user’s field of view so a user may request access to both of them. VACMaps appropriately denies access to the points located in the private bystander spaces while allowing access to map points in the common area.

5.3 Performance and Scalability

We now evaluate VACMaps’s performance and show how it scales to increasing numbers of policies and virtual spaces.

5.3.1 Can VACMaps Be Fast Enough in Practice?

Ideally, access control should not add much overhead to the run time of localization and mapping. In this experiment, we evaluate the time needed for VACMaps to handle access requests. We use the synthetic house dataset (Figure 6) as the testing environment. We define a series of access policies that allows a user access to some of the rooms while denying the user access to others. We then follow the simulated tour (Figure 6b) and send access requests for all extracted feature points within a frame as the user to VACMaps. We then measure the time it takes for VACMaps to process all access request originating from each frame.

The result is shown in Figure 8a. As the number of extracted feature points increases, the total processing time for each frame increases linearly. Since access requests can essentially be handled in a parallel manner, the optimized processing time can be much shorter in practice. Since we expect to see many points within the same space in a single frame, we also implement an LRU cache that stores the results of recent access rights queries. The performance gain of the cache denote by red dots in Figure 8a shows the cache roughly halves the processing time.

5.3.2 Does VACMaps Scale to Handle Large Maps and Complex Policies?

Localization and mapping must be a service that can scale to potentially thousands of physical spaces with arbitrarily complex access policies. To evaluate the scalability of VACMaps, we evaluate the performance of VACMaps for larger maps with many physical spaces, spaces associated with lengthy access control policies, and spaces whose access policy involves a lot of users.

First, we study the run time of VACMaps as the number of policies over three rooms. Notice that each room inherits the policy of its enclosing space. Also, Alice still does not have access to the bathroom since her access rights are “overridden” by the deny policy on the bathroom that applies universally to all principals. For a query point on the second floor, its relevant policies are represented as an SMT formula (\(f_{\text{first policy}} \lor f_{\text{second policy}} \lor \neg f_{\text{third policy}}\)).

Fig. 5. Spatial hierarchy, access policy, and SMT formula translation of policy on the example house dataset. Here the master bedroom is the rightmost bedroom on the second floor of the house, small bedroom 2 is one of the small bedrooms on the second floor, and guest bathroom is the bathroom on the first floor. For readability we use an abbreviation \((x, y, z) \in B\) to represent the conjunctive formula \(t_d \leq x \leq r_d \land \ldots\) specifying 3D point with coordinate \((x, y, z)\) must lie within an axis-aligned box \(B\).

(a) Hierarchy of rooms and spaces in our single-family home dataset. Shaded boxes correspond to rooms/spaces for which we want to implement certain access-control mechanisms that prevent certain residents of the house from mapping these rooms.

(b) An example set of access control policies for the single-family home dataset. The first policy grants Alice read access to all spaces in the house. The second policy gives Bob read access to the recreation area and a small bedroom on the second floor given that Bob is in the house and the current time is after 9 am. The third policy prevents anyone from accessing the bathrooms.

(c) Example SMT formula translation for the policies over three rooms. Notice that each room inherits the policy of its enclosing space. Also, Alice still does not have access to the bathroom since her access rights are “overridden” by the deny policy on the bathroom that applies universally to all principals. For a query point on the second floor, its relevant policies are represented as an SMT formula \(f_{\text{first policy}} \lor f_{\text{second policy}} \lor \neg f_{\text{third policy}}\).
with each cube a simple access policy. Then we measure the time for VACMaps to serve an access request to a random cube. The results in Figure 8a show that the run time does not increase significantly even if we have more than 100,000 spaces. We attribute this directly to an efficient implementation of the spatial hierarchy organization that VACMaps employs using 3D segment trees; this implementation enables VACMaps to reduce the complexity of looking up relevant spaces for a 3D point to $O(\log n) + m$ where $m$ is the output size, i.e., number of spaces actually containing the point. As a result, because of the logarithmic complexity, the resulting performance is effectively the same even as the number of space increases.

We also evaluate the performance of VACMaps as the complexity of policies increases. We create $n$ unit cubes as spaces and associate cube $n$ with a policy of length $O(n)$. This policy is a large disjunction of clauses that all evaluates to false. The system needs to evaluate each clause so we expect the processing time to be $O(n)$ for a single access request against cube $n$. The results in Figure 8b illustrate that the run time is roughly linear as the number of policies increases.

Finally, we evaluate the performance of VACMaps as the number of relevant users grows. We create 1 unit cube as the only space under consideration and associate with it $n$ policies, each mentions a different user. This in principle has the same effect as increasing the policy length and we indeed observe a similar trend in Figure 8d.

Overall, we find that the scalability of VACMaps across number of features per frame, virtual spaces, policy count, and users is reasonable.

5 The set of relevant users with respect to a space contains all principals mentioned in the policies for that space.

5.4 Auditing and Verifying Access Permissions

While VACMaps takes access policies as input to verify and enforce access control requests, it does not reason about whether a user properly specified policies in the first place. This leaves it entirely up to the user to define intended access policies. Specifying policies can be challenging as it requires meticulously combining conditions across spaces, users, and time. While VACMaps cannot infer user intent, it can aid users in properly setting and debugging policies.
Table 1. Description of common access control scenarios used to verify VACMap’s basic functionality and correctness.

| Scenario                        | Description                                                                 | Expected Access Behavior                                                                 |
|--------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Conservative default policy    | A space does not have any defined access policy associated with it.          | All users are by default denied access to this space.                                    |
| Private spaces                  | User A is inside their own private space.                                    | Only user A should be allowed access to this space.                                      |
| Shared private spaces           | A user is going to the restroom.                                             | User should be denied access for mapping and localization.                               |
| Bystander spaces                | User A is walking by user B’s house where the windows are open and A can see into B’s private space. | User A should be denied the ability to map user B’s private space.                       |
| Localize with another user’s map| User A tries to localize himself into an environment using map points generated by user B. User B wants to keep their map data private though. | User A should be denied access to user B’s map.                                          |
| Denying friends of friends access | User A invites a friend user B who invites user C who is a friend of B but not a friend of A. User A trusts user B but not user C with mapping the house. | User B should be able to map and localize but user C should be denied access.            |
| Private space map contamination | User A uses a compromised device to inject map points into user B’s private space. | Access requests by user A to modify user B’s map should be denied.                        |
| Changing or revoking access policies | User A wants to change the condition under which a friend B can map A’s house, and wants to revoke user C’s access to map A’s house. | Once the policy change request is handled, user B and C’s access rights to A’s house are modified and enforced through the access control system. |

We enable auditing of privacy policies over spaces leveraging the logic reasoning and SMT formula semantics that VACMaps is built upon. At a high level, the auditing of policy configurations of a space is done by constructing (potentially a series of) SMT queries against the formula representation of policies. This feature can detect potential policy misconfigurations in existing policies or prevent problematic policies from being introduced in the first place. Table 2 shows a set of common scenarios that a user may want to audit for their virtual spaces and how we implement these audits within VACMaps. For example, a user configuring access policies for their home may want to restrict access to their living room to family members and thus want to see who has access after entering the policy. If access is overly permissive, this audit will reveal which other users have access. The owner can then use this information to fix policy misconfigurations. As another example, we consider the effect of pre-existing deny policies. Since deny policies override allow policies, new policies that try to allow access to a subspace might not have any effect. In practice, it is likely that a space will be subject to many policies and it can even inherit policies from enclosing spaces, which will make it challenging for most users to understand why their new allow policy is not effectual. Using VACMaps’s automated reasoning we can detect these ineffective policies so that the user will be prompted to review and modify the deny policy in order for the new allow policy to work as expected.

6 Related Work

This section highlights related work across security and privacy, computer vision, and formal methods.

6.1 Security and Privacy Approaches to Access Control

AR security and privacy concerns are not a new concept in the research literature. Roesner et al. [45] point out that AR systems enable novel attacks against users and pose new threats to users’ and bystanders’ privacy. Similarly, De Guzman et al. [46] surveys recent developments in the security and privacy of mixed reality (MR) systems by classifying them based on a data-centric scheme. Chen et al. [47] demonstrates that an attacker could use the video feed and depth information captured by an AR device to recover victim’s password input on a touch screen and proposes designing defenses tailored to this. Lebeck et al. [48] perform a qualitative lab study on AR headset users and identifies the need for access control among users to manage shared physi-
6.2 Computer Vision Approaches to Access Control

Recent work in computer vision \cite{50, 51} studies how photos and videos taken in public places might pose a potential privacy risk to bystanders. The most relevant work to ours in the vision community is by Templeman et al. \cite{52} who present a technique based on image classification that identifies where an image was taken and recognizes if this image concerns sensitive spaces like bathrooms or bedrooms. This offers the AR device user the capability to “blacklist” these spaces by defining their own access control policies. However, this technique only supports simple policies as a list for forbidden or blacklisted spaces.

6.3 Formal Methods and Access Control

Although there exist standardized frameworks for access control languages, for example XACML\cite{53}), various domain-specific languages (along with formalization of their semantics) are often designed to target different application domains. Guelev et al. \cite{54} presents a loop-free programming language and its formal semantics which correspond to steps that a user could take to try to gain access to a resource. The authors then move on to reasoning about whether a program exists to prove that whether or not a user could eventually get access to a resource. Hughes and Bultan \cite{55} formalizes access policies written in XACML format as SAT formulas and invokes a SAT solver to check if policies satisfy a partial order relationship. Dougherty et al. \cite{56} studies access control policies in a dynamic environment and identifies a few decidable analyses in first-order temporal logic. Backes et al. \cite{57} formalizes semantics of the Amazon Web Services (AWS) policy language and introduces an analysis tool that encodes semantics of access policies associated with AWS resources into SMT formulas. The tool then invokes Z3 \cite{58} (along with a customized theory solver for strings) to verify properties of AWS access policies. In contrast, our work is among the first to apply such access control and formal methods techniques to localization and mapping for AR.
(a) Run time of VACMaps to process one frame as the number of extracted feature points increases in the image, with (red dots) and without (blue dots) the LRU cache implementation.

(b) The spatial hierarchy implementation in VACMaps scales to handle a large number of spaces: processing time does not change much even for 100k spaces.

(c) VACMaps scales to handle complex policies. Processing time grows linearly when policy length is large enough. It is likely that the reason for the smaller slope in the beginning is that solvers implement optimizations for short formulas that are not possible for long formulas.

(d) VACMaps scales linearly to handle a large number of relevant users. Processing time is linear w.r.t. number of relevant users, as expected.

Fig. 8. VACMaps performance and scalability with (a) more features per frame, (b) more virtual spaces, (c) longer policies, and (d) more relevant users.

Table 2. Examples of auditing functionalities enabled by VACMaps. VACMaps can craft queries to the SMT engine to execute checks for misconfigurations of interest. The results can then be used to help a user audit potential problems in policy configurations.

| Query                                                                 | Implementation                                                                 |
|-----------------------------------------------------------------------|--------------------------------------------------------------------------------|
| List all users who have access to a space under certain conditions.   | Query the solver for a satisfying assignments to the variables and output the principal, add a blocking clause to the policy formula to prevent the same user being selected again. Repeat until the formula becomes unsatisfiable. |
| Are policies for a non-public space too weak so that everyone could access it? | Check if the formula representing a weak policy stating that everyone can access this space implies the formula encoding the existing policies for this space. |
| Are policies for a private space too strong so that even the owner could not access it? | Check if the formula encoding the policy for the space conjuncted with a clause that specifies the principal equals the owner of the space is satisfiable. |
| Does a new “allow” policy really extend access rights to some space?   | Check if the original policy formula conjuncted with the new policy formula is weaker than the original formula. The check is non-trivial since deny policies override allow policies regardless of the ordered in which they are added. |
| Is there a user who is allowed access to a space in some policy but denied access to the same space by another policy? | Collect the set $S$ of all principals that appear in the allow policies for a space. Any deny policy must have an SMT encoding with form $\neg Q$. We just check if any $n \in S$ can make the formula $Q \land \neg \text{principal} = n$ satisfiable. |
| Are policies for a space more permissive than its enclosing spaces?    | Check if the formula representation for the space’s policies is weaker than that for enclosing spaces. |
7 Conclusion and Future Work

This work presents VACMaps which is an access control system that provides provably correct access decisions for AR localization and mapping using formal methods. VACMaps enables automated reasoning over access policies by introducing a DSL for policy writers and its corresponding semantics via the SMT encoding of the policies. We also show that VACMaps is both fast and scalable, and that it can also be used to audit misconfigurations in access policies.

VACMaps focuses on localization and mapping data, however we expect that similar access control needs will arise for other AR data structures and use cases in the future. Additionally, we hope to introduce a DSL that allows users to write more robust access policies against estimation errors that are inherent to localization and mapping algorithms.

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