A guiding famework for vetting the Internet of things

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A Guiding Framework for Vetting the Internet of Things

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Abstract

Like any emerging and disruptive technology, multiple obstacles are slowing down the Internet of Things (IoT) expansion for instance, multiplicity of things' standards, users' reluctance and sometimes rejection due to privacy invasion, and limited IoT platform interoperability. IoT expansion is also accompanied by the widespread use of mobile apps supporting anywhere, anytime service provisioning to users. By analogy to vetting mobile apps, this paper addresses the lack of principles and techniques for vetting IoT devices (things) in preparation for their integration into mission-critical systems. Things have got vulnerabilities that should be discovered and assessed through proper device vetting. Unfortunately, this is not happening. Rather than sensing a nuclear turbine's steam level, a thing could collect some sensitive data about the turbine without the knowledge of users and leak these data to third parties. This paper presents a guiding framework that defines the concepts of, principles of, and techniques for thing vetting as a pro-active response to potential things' vulnerabilities.

Keywords: Internet of Things, Security vulnerabilities, Vetting, and Atomic/composite duties.

1. Introduction

In the 21st century, security triad formed by confidentiality, integrity, and availability (CIA) in addition to user privacy, are among many pressing concerns that the Information and Communication Technology (ICT) community is actively examining [1]. The number of misuse and fraudulent cases related to the ICT are on the rise, suggesting the need for an immediate revision of existing practices, techniques, and tools. According to the Australian Institute of Criminology, the estimated value of internal fraud against the Commonwealth has steadily increased from $1.9 million to $3 million between

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2008 and 2011. To mitigate some of these cases, an option is to **vet** ICT applications prior to their integration into day-to-day (sometimes critical) business operations. By vetting, we mean ensuring their safety and compliance with relevant regulations. Mobile apps exemplify ICT applications, whose rapid and uncontrolled widespread use has become a major concern to policy makers. As of September 2019, there were 2.7 million apps posted on *Google Play Store* and 2.46 million apps posted on *Apple's App Store*, which are the 2 leading app stores in the world [2], with the number of connected devices set to top 20 billion by 2023 [3].

In conjunction with the mobile apps "fever", we observe some early signs of another "fever" that the Internet of Things (IoT) could end-up catching. According to Gartner, 6.4 billion connected things were in use in 2016, and this number is projected to reach 20.8 billion by 2020 [4], [5]. Accordingly, the total economic impact of IoT will reach between $3.9 trillion and $11.1 trillion per year by 2025 [6]. This rapid increase in the number of things needs to be closely monitored to avoid a "boom" in privacy breaches, identity thefts, confidentiality deceptions, etc.

Things in an IoT ecosystem have some unique features that make them different from other components such as reduced size, restricted connectivity, continuous mobility, limited energy, and constrained storage [7]. On top of these features, things' plethora of uses lead to the generation of rich and large volume of (unstructured) data that need to be processed in compliance with requirements such as safety, security and privacy. The complexity of these features mixed with these different uses raises a number of challenges related to how safe things are or should be. In this context, $\mathcal{V}$etting IoT ($\mathcal{V}$IoT) is appropriate for ensuring things' "good conducts" before allowing them to collect, process, and distribute data without raising any concerns. However, there is a limited number of R&D initiatives on $\mathcal{V}$IoT, which is accentuated by the heavy dependence of ICT practitioners on the security claims of things' vendors [8].

By analogy to mobile apps vetting, we aim to develop a guiding framework for $\mathcal{V}$IoT. The objective is to verify things' "good conducts" and identify the vulnerabilities that could lead to misconducts. Examples of vulnerabilities could be the excessive use of resources, data sharing with unauthorized parties, and changes in initial configurations. In this paper and in line with our ongoing agenda on IoT [9, 10], we refer to things' actions as duties and categorize them into atomic and composite [1]. This categorization permits the fine-tuning of the vetting according to each duty's characteristics and whether the duties originate from the same or different things. Our contribution is manifold, including (*i*) the

[1] Atomic/Composite duty is similar to Component/Composite service adopted by the service computing community [11]

definition of vetting in the context of IoT, (*ii*) the identification of vulnerabilities for atomic duties and composite duties, (*iii*) the analysis of the consequences of vulnerabilities on the completion of duties, and (*iv*) the demonstration of the vetting through a proof of concept.

The rest of this paper is organized as follows. Section 2 discusses initiatives for vetting mobile apps. Section 3 identifies existing gaps in vetting things. Section 4 details the process of preparing things for vetting. This consists of identifying their duties along with analyzing the impact of vulnerabilities on these duties that things are expected to achieve. Prior to concluding in Section 6, conceptual details about the framework along with the results of the experiments are presented in Section 5.

2. Vetting mobile apps

According to the US National Institute of Standards and Technology (NIST) [12], there is a need to secure mobile apps from vulnerabilities and defects; apps are used by all people and all organizations. To satisfy this need, a strict vetting process would ensure that mobile apps comply with an organization's security requirements and are to a certain extent free of (serious) vulnerabilities. These requirements could be related to origin, data sensitivity, and target environment and could be decomposed into (*i*) general with respect to some existing standards and best practices, such as those specified by NIAP, OWASP, MITRE, and NIST, and (*ii*) specific with respect to some internal policies, regulations, and guidelines. Factors that could be the cause of app vulnerabilities include design flaws and programming errors, which could have been inserted intentionally or inadvertently [12]. Depending on the risk tolerance of an organization, some vulnerabilities might be more serious than others, suggesting the need for a contextualized vetting process. Vetting could occur throughout an app's lifecycle, which consists of development, acquisition, and deployment stages and would cover correctness testing, source and binary code testing, and static and dynamic testing.

In [8], Quirolgico et al. mention that millions of apps for mobile devices are available through commercial stores and open repositories. Because of their low cost and widespread, the threats of the vulnerabilities of these apps could be far greater than those of traditional computers. Because some vulnerabilities of mobile apps are unique, the study insists on the urgency of developing a quick and cost efficient vetting process.

In [13], He et al. analyze malware attacks on smartphones and suggest a two-level defense strategy that aims at preventing malware from entering smartphones and determining whether appropriate tools should detect and remove them. However, this may not always be successful due to the rapid changes in malware behavior and therefore, more sophisticated tools need to be quickly developed while considering smartphones' limitations. He et al. recommend collaboration between apps' administrators, phone users, and application developers to detect and prevent malware threats. They highlight the need for a strict app vetting on the server-side for removing any malicious apps from the market using cloud-based scanning engines. Finally, He et al. conclude by suggesting new research directions related to the issues of (1) how to systematically collect data of emerging malware; (2) how to develop techniques and tools to associate new attacks with those already recorded; (3) how to uncover unknown malware; and (4) how to make a paradigm shift that will involve advertisers as defenders, too. The lack of datasets about new vulnerable applications is also discussed by Nagappan and Shihab in [14]. They address the need for more sophisticated lightweight tools that would prevent malicious code from getting into smartphones through mobile app stores.

In [15], Chen et al. propose mass vetting (MassVet), a lightweight mechanism that is capable of quickly discovering unknown malice at a large scale (e.g., *Google Play Store*). The authors use an app's view structure and navigation relations among views to produce a view graph whose nodes correspond to view items (active widgets) and arcs between nodes show navigation paths. These graphs are further compared with those that original apps on the market have.

The fields of mobile computing (exemplified with mobile apps) and IoT (exemplified with hundreds types or models of device) present many similarities in terms of affordability, wide use, and limited control; thus, they should benefit from each other. Guidelines for vetting mobile apps already exist and would constitute a good source for developing the same for IoT. The next section identifies the gaps in current research related to vetting IoT.

3. Gaps in vetting IoT

Compared to vetting mobile apps (Section 2), there is a major gap in ($\mathcal{V}$IoT). In addition to Section 1's obstacles that undermine IoT, this gap is also due to the nature of IoT. IoT mixes physical processes with cyber connectivity, making it different from other software-related disciplines [16]. The first set of references that we reviewed are more concerned with the security and privacy of IoT applications than with developing a comprehensive guide for vetting things that would reveal their vulnerabilities. Meanwhile, the second set of references run tests to identify vulnerabilities of IoT devices that are already in operation [16]. There is a consensus that IoT vastly impacts the way we view, use, and interact with smart devices [17]. However, security remains a concern that could turn IoT misuse into a serious problem; such devices collect and use users' personal data without their permissions. McKinsey argues that security may represent the greatest obstacle to IoT growth [18]. In [19], Creager discusses methods for detecting IoT devices' suspicious activities. Devices are monitored for proper behavior, and those that show signs of having been interfered can have their behaviors mitigated and their security issues eliminated.

In [20], Celik et al. examine the security and privacy of IoT applications using a program-analysis technique. They use the examples of unlocked doors when nobody is at home and turned-off heaters in cold weather. Both examples illustrate risks for the safety of people and their assets, calling for appropriate and prompt measures. Despite those risks, Celik et al. do not target IoT but, IoT platforms that are used to develop them and the IoT applications that manage them. The considered IoT platforms are Samsung's SmartThings, Apple's HomeKit, OpenHAB, Amazon AWS IoT, and Android Things.

In line with the work of Celik et al., Fernandes et al. [21] look into data protection in the context of IoT, in general, and mobile apps associated with IoT, in particular. They argue that permission-based access control over sensitive data is not enough once an app gains control over data. Apps should make their data-use patterns explicit so that these patterns are enforced (deviations are not allowed) at runtime when sensitive data is used. Fernandes et al.'s system, known as FlowFence, enables robust and efficient flow control between sources and sinks in IoT applications by creating a data-handling mechanism for privacy protection purposes. FlowFence focuses partially on data leakage prevention where the overall IoT device behavior is not considered.

In a 2018 report by KEYFACTOR [22], the authors discuss cases of IoT devices that have been subject to attacks although these devices were critical to humans' lives. Vetting IoT devices would have helped prevent or at least reduce such cases by revealing their vulnerabilities ahead of time. In the healthcare domain, in 2017, the US Food and Drug Administration (FDA) recalled 465K pacemakers after discovering security flaws that could allow hackers to drain device batteries or send malicious instructions to modify a patient's heartbeat. Vetting pacemakers could have prevented such cases too. Similar news were reported in the automotive industry when a Jeep Cherokee was hijacked turning off the transmission while the vehicle was on the freeway.

Among the different works that we reviewed, the works of Palavicini Jr. et al. [23] and Siboni et al. [24] overlap with our objectives. On the one hand, Palavicini Jr. et al. apply symbolic analysis to vet, in a semi-automated way, Industrial IoT (IIoT) firmware using *angr*, a UC Santa Barbara binary analysis framework [25], and *Mecanical Phish*, a component from the same university's cyber reasoning system, to

Table 1: Summary of the common reviewed state-of-the-art research that highlights the scopes, contexts, and main contributions. ● means fully covered, ◑ means partially covered, and □ means uncovered.

	Scope			Context			
Literature	Security	Privacy	Vetting	Software (Apps)	Hardware	IoT	Contributions
He et al. [13]	◑	□	◑	●	□	□	Future directions
Nagappan and Shihab [14]	◑	□	◑	●	□	□	Reviews and recommendations
Chen et al. [15]	●	□	◑	●	□	□	MassVet technique
Celik et al. [20]	●	●	◑	●	□	●	Challenges and opportunities
Fernandes et al. [21]	◑	◑	□	●	□	◑	FlowFence system
Palavicini Jr. et al. [23]	◑	□	●	●	◑	◑	Semi-automatic firmware vetting
Siboni et al. [24]	●	◑	●	●	◑	●	Security testbed framwork

perform the semi-automated analysis of IIoT. The authors mention that embedded systems and IIoT devices are rapidly increasing in number and complexity. As a result, cyber-physical attacks have become omnipresent, causing economic and physical damages. They also mention that the firmware for these systems has become difficult to analyze when searching for malicious functionalities. Their approach consists of 3 steps: preparation of the firmware image for loading into the *angr* framework, emulation for verification of discovered vulnerabilities, and analysis of the firmware sample "angr style".

On the other hand, Siboni et al. [24] discuss a security testbed for IoT devices that iTrust Lab has developed. First, they report on the experience of using an IoT search engine, SHODAN [26], to discover vulnerabilities of IoT devices. It is worth noting that this experience targeted devices that were already in operation, while we insist that vetting aims at detecting vulnerabilities prior to putting devices into operation. The proposed testbed emulates different types of testing environments that simulate the activity of multiple sensors and perform predefined and customized security tests along with advanced security testing analysis. Siboni et al. consider 4 security aspects of IoT devices: *architecture*, which investigates attacks on hardware and software; *network connectivity*, which investigates attacks on data distribution; *data collection*, which that investigates data collection with regard to privacy invasion and information theft; and, finally, *countermeasures and mitigation*, which that investigate how to reduce the security and privacy risks that IoT devices could cause. According to Siboni et al., the proposed framework requires further improvements to support the full operational capability so that the entire IoT environment is considered. In addition, the framework uses different open source tools to simulate real operational environments and to run security tests. These tools may need a vetting process for itself, continuous updates, and special configuration from device-to-device, which makes the proposed framework complex.

Table 1 summarizes the scopes, contexts, and contributions of the reviewed state-of-the-art research. The table clearly demonstrates that very few papers focus on the IoT vetting process by introducing security testing frameworks. The rest of the research either focuses on mobile apps or introduces a partial vetting process or partially covers security and privacy aspects. In common, the reviewed literature considers testing IoT devices that are already in operation, although this research aims for a vetting framework that detects security vulnerabilities before taking the device into operation.

4. Preparing things for vetting

According to Crews and Mangal [27], the massive arrival of smartphones and mobile apps has triggered a "mini-revolution" in the software engineering discipline. Some concepts, principles, and practices, such as those related to testing, have been adjusted. Touchscreen gestures, location awareness, and orientation need to be tested differently. The same is valid when testing and vetting IoT smart devices. We expect that IoT features in terms of reduced size, restricted connectivity, continuous mobility, limited energy, constrained storage, and additional features that Kamrani et al. [28] discuss will trigger a similar "revolution". *"The things in the Internet of Things (IoT) can get personal. They can be in your home, your car, and your body. They can make your living and working space smart, and they can be dangerous to your health, safety, and liberty. $\cdots$ Is our future a brave new world or a dystopian nightmare? Who decides?"* [29].

4.1. Overview

By analogy to the NIST definition of the app vetting process [12], the IoT vetting process would be a sequence of activities that an organization would carry out to declare if a thing is "clean" with respect to some IoT safety and security requirements. Our sequence of activities represented in Figure 1 would consist of (*i*) defining things' duties that would be subject to vetting, (*ii*) identifying the vulnerabilities that would affect these duties, (*iii*) analyzing the impact of these vulnerabilities on these duties, and (*iv*) developing guidelines and/or recommending techniques to address these vulnerabilities. The first two steps in Figure 1 are already discussed in [9, 10]. Therefore, this article focuses on the impact of vulnerabilities on duties to initiate the development of guidelines against these vulnerabilities.

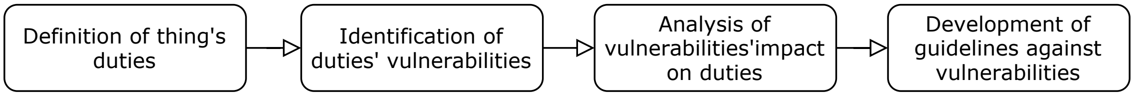

Definition of thing's duties
Identification of duties' vulnerabilities
Analysis of vulnerabilities'impact on duties
Development of guidelines against vulnerabilities

Figure 1: General representation of the $\mathcal{V}$IoT process

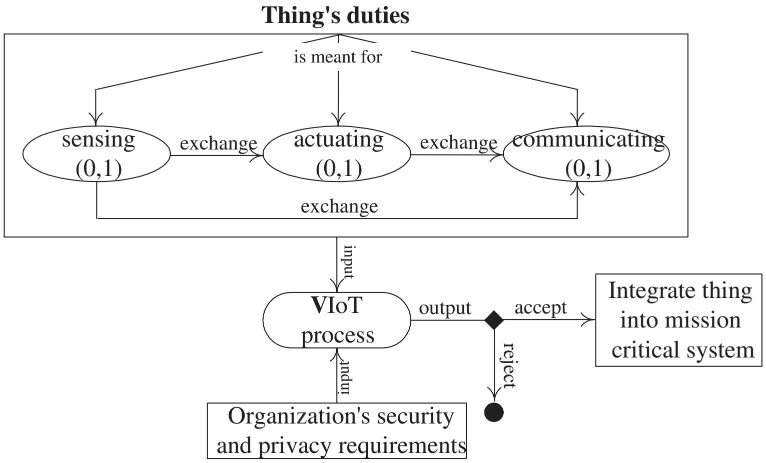


Figure 2: Atomic duties of a thing

4.2. Duties of things

In a previous work [10, 30], we identified 3 atomic duties that would capture a thing's capabilities in terms of *sensing* (collecting and temporarily storing data), *actuating* (processing/acting upon data), and *communicating* (sharing/distributing data). A duty is either enabled or disabled ((0,1) in Figure 2) according to the requirements and needs of the under-development IoT applications. Our duty categorization overlaps to a certain extent with first, Celik et al.'s sensor-computation-actuator cycle that structures the design of IoT systems' apps [20] and second, the IoT device capabilities of [31].

Simply put, a thing senses the cyber-physical surrounding so that it generates and (temporarily) stores (raw) data; a thing actuates data including those that are sensed; and a thing communicates with the cyber-physical surrounding the sensed and/or actuated data. Accepting data and/or commands from external parties (e.g., other things) is also taken care of by the communicating duty, but this process is not further discussed in this report. It is worth noting that a thing's sensing, actuating, and communicating duties can be composed together as per the following 4 representative cases (other cases, such as Communicating, Actuating and Communicating, Actuating, Sensing are not discussed):

1. Sensing, Actuating, Communicating: sensed data are passed on to actuating; and the data that result from actuation are passed on to communicating for distribution.

2. Sensing, Actuating: sensed data are passed on to actuating; and the data that result from actuation are finals.

3. Sensing, Communicating: sensed data are passed on to communicating for distribution.

4. Actuating, Communicating: data that result from actuating are passed on to communicating for distribution.

Figure 3 is the duty model representation referring to one super-class, Duty, which would describe the common characteristics of all the duties, such as identity (id_duty), name (name_duty), type (type), and resources to consume when performing the duty (res). Duty is specialized into Sensing, Actuating, and Communicating. Sensing class describes elements such as frequency (freq_sensing) and sensed data (data). Actuating class describes elements such as necessary time (latency) and actions (actions) required to take over data (data). Communicating class describes elements such as time (timestamp), performed action (action), which could be either "receive" or "send", and the involved things (things) in this duty. Data class of a thing (thing) describes elements such as the attribute (attribute, e.g., response time), value (value_data), and validity (validity). Resource class describes elements such as identity (id_res), name (name_res), and value (value_res). Finally, the Thing class defines the characteristics of the thing that performs duties such as identity (id_thing) and description (des_thing).

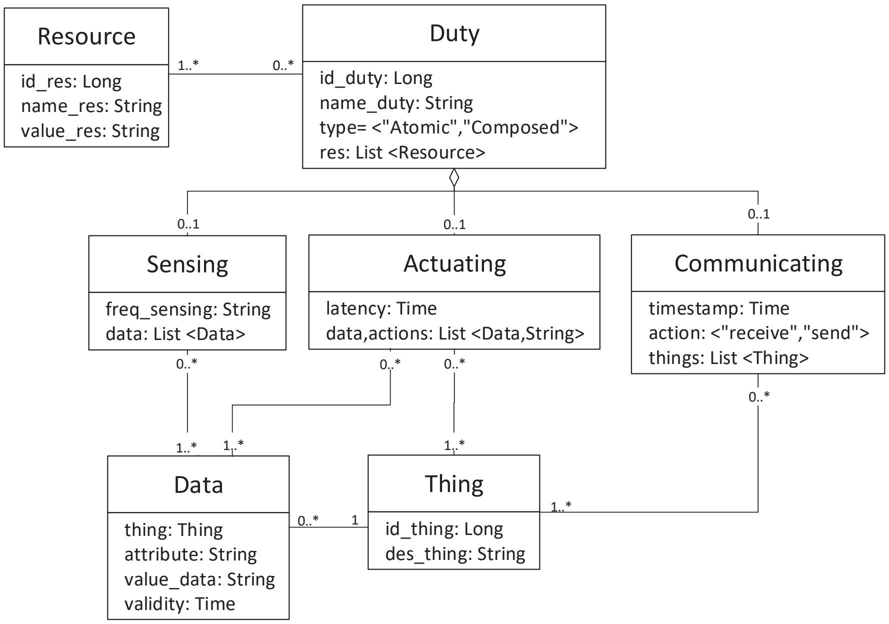


Figure 3: Duty model

4.3. *Analysis of vulnerabilities of duties*

As per Figure 1, our *v*IoT process proceeds with defining the duties of things and then, identifying potential vulnerabilities that could negatively impact these duties. Although some vulnerabilities that could be sources of attacks havealready been identified in the context of the OWASP IoT project [32] (Table 2), we find these vulnerabilities generic and not related to the duties of things. To address this limited focus, we have developed different questions[2] that would expose vulnerabilities, as per Table 3, where V_i^x is the i^{th} vulnerability related to either an atomic or a composite duty x, and $x \subset$ {s, a, c, sac, sa, sc, ac} (s: sensing, a: actuating, and c: communicating). Only the questions for atomic duties are presented.

Table 2: Common security vulnerabilities in the IoT paradigm in the context of the OWASP IoT project

Vulnerability	Attack surfaces	Summaries
Username enumeration	Administrative interface	Ability to collect a set of valid usernames by interacting with the authentication mechanism
	Device Web interface	
	Cloud interface	
	Mobile applications	
Weak passwords	Administrative interface	Ability to set account passwords to ’1234’ or ’123456’, for example Usage of pre-programmed default passwords
	Device Web interface	
	Cloud interface	
	Mobile applications	
Account lockout	Administrative interface	Ability to continue sending authentication attempts after 3 - 5 failed login attempts
	Device Web interface	
	Cloud interface	
	Mobile applications	
Unencrypted services	Device network services	Network services are not properly encrypted to prevent eavesdropping or tampering by attackers
⋮	⋮	⋮

Questions (Q) that can be raised during the vetting of sensing include but are not limited to Q_1: does sensing target living (e.g., persons) and/or non-living things (e.g., rooms)? What is the sensing about (e.g., ambient temperature, wind speed, and heartbeat)? Q_2: does sensing target indoor, outdoor, or both? Q_3: what is the frequency of sensing (e.g., continuously, at regular intervals, or trigger-based)? Q_4: who configures sensing (e.g., frequencies, service periods, or authorized recipients)? Does configuration need to occur from a specific location and/or using a specific device? Q_5: what is the resource consumption level of sensing? Also, is there any threshold that would indicate overconsumption and hence, trigger alarms? And, Q_6: are there traces of tracking sensing using logs, for example? If yes, how are the traces safeguarded?

Questions (Q) that can be raised during the vetting of actuating include but are not limited to Q_1: can a thing cancel and/or compensate the outcomes of actuating? If yes, does it need any approval? Q_2: what is the frequency of actuating (e.g., continuously, at regular intervals, or trigger-based)? Q_3: who configures actuating in terms of frequencies, service periods, etc.? Does configuration have to happen from a specific location and/or using a specific device? Q_4: what inputs does actuating require? What outputs

[2] The questions are part of a tip-sheet similar to the one available at https://tinyurl.com/thpzmc3.

does actuating produce? Q_5: are there traces of tracking actuating using logs, for example? If yes, how are these traces safeguarded? And, Q_6: what is the resource consumption level of actuating? And, is there any threshold that would indicate overconsumption and hence, trigger alarms?

Questions (Q) that can be raised during the vetting of communicating include but are not limited to Q_1: what interaction protocol does communicating use? Also, is this protocol secured? Q_2: what interaction mode does communicating use (e.g., synchronous *versus* asynchronous and point-to-point *versus* multi-point?) Q_3: what is the frequency of communicating (e.g., continuously, at regular intervals, or trigger-based)? Q_4: who configures communicating in terms of frequencies, mode, service, etc.? Does configuration have to happen from a specific location and/or using a specific device? Q_5: to whom does thing send data (e.g., persons, systems, or both)? Are there guarantees that data recipients do not share it further without approval? Q_6: is data communicated immediately with authorized parties or cached for later sharing? Also, if data is classified, what measures are used for achieving this? Q_7: what is the resource consumption level of communicating? Also, is there any threshold that would indicate overconsumption and hence, trigger alarms? And, Q_8: are there traces of tracking communicating using logs, for example? If yes, how are these traces safeguarded?

4.4. Impact of vulnerabilities on duties

In this part of the paper, we examine the impact of vulnerabilities on atomic and composite duties. To this end, we capture the successful completion of a duty using a state diagram and then, enrich this diagram with special notations to illustrate how a duty could deviate from this completion because of vulnerabilities. We see deviations as vulnerability's side effects.

4.4.1. Atomic duties

Sensing. Figure 4 is a state diagram that tracks the progress of the sensing duty towards successful completion. Using this diagram's states and transitions, we develop what we refer to as normal-progress cycle of a duty (plain lines in Figure 4). We also enrich this diagram with necessary states and/or transitions to represent deviations from this cycle that correspond to side effects of vulnerabilities (dashed lines in Figure 4).

On the one hand, in a normal-progress cycle, the states are not-activated (the sensing duty is not available), activated (the sensing duty is being configured), operated (a composed state where the

Table 3: Sample of vulnerabilities of things per duty

Type	ID	Description
Atomic	V_1^s	Changing sensing frequency(ies) without approval
	V_2^s	Tampering sensing's approved resource consumption-level so, this over consumption gets unnoticed
	V_3^s	Infinite suspension of sensing duty
	V_4^a	Changing actuating frequency without approval
	V_5^a	Altering inputs purposely
	V_6^a	Infinite suspension of actuating duty
	V_7^c	Communicating differently from the claimed frequency
	V_8^c	Using a different protocol from what is claimed
	V_9^c	Unauthorized party proceeds with communicating using a non-acceptable device
	V_{10}^c	Interrupting communicating without resumption
Composite	V_{11}^{SA}	Changing sensing frequency(ies) without approval or (un)synchronized sensing and actuating though it is not mandatory
	V_{12}^{SA}	Interrupting sensing or actuating without resumption
	V_{13}^{SA}	Altering sensed input, which would impact the sensed input to actuate
	V_{14}^{SC}	Changing sensing frequency without approval, which would impact the frequency of the sensed content to communicate
	V_{15}^{SC}	Interrupting sensing or communicating without resumption
	V_{16}^{SC}	Unauthorized party proceeds with sensing and communicating configuration using a non-acceptable device
	V_{18}^{AC}	Changing actuating frequency(ies) without approval or (un)synchronized actuating and communicating though it is not mandatory
	V_{19}^{AC}	Interrupting actuating or communicating without resumption
	V_{20}^{AC}	Altering received input
	V_{21}^{AC}	Unauthorized party proceeds with communicating using a non-acceptable device
	V_{22}^{SCC}	Change in sensing or communicating frequency or resource consumption of the sensing duty
	V_{23}^{SCC}	Infinite suspension of sensing duty or the communicating duty in the sensing duty or the communicating duty in one of the two things
	V_{24}^{SCC}	Altering received input

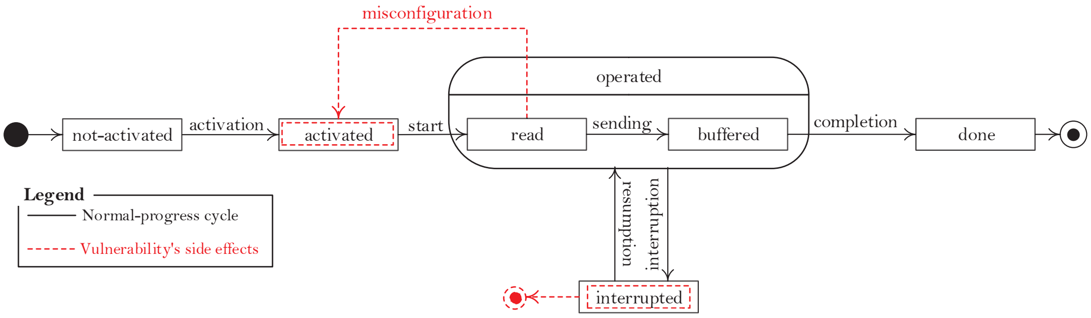


Figure 4: Enriched state diagram of the sensing duty

sensing is taking place in terms of reading and buffering[3]), done (the sensing is complete), and interrupted (the sensing is put on-hold and then resumed). On the other hand, the transitions connecting these states together are activation, start, sending, interruption, resumption, and completion.

Vulnerability's side effects correspond to 2 states, namely, activated (the sensing duty is misconfigured) and interrupted (the sensing is put on-hold indefinitely), and 1 transition, namely, misconfiguration. We associate misconfiguring sensing with 2 vulnerabilities, namely, change in sensing frequency (V_1^s) and tampering resource-consumption level (V_2^s), and we associate indefinite on-hold with 1 vulnerability, namely, infinite suspension of sensing (V_3^s).

Actuating. Similar to sensing, we develop the normal-progress cycle of the actuating duty (plain lines in Figure 5) and identify the side effects of vulnerabilities that this duty could be subject to (dashed lines in Figure 5).

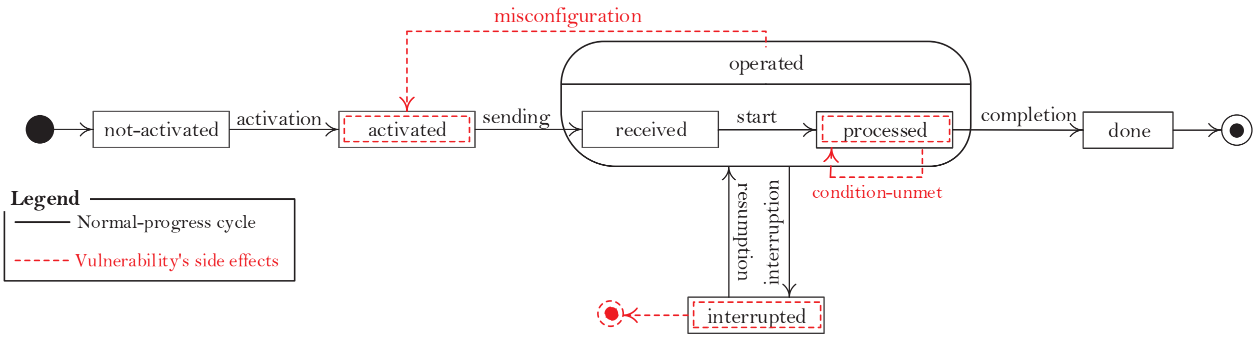


Figure 5: Enriched state diagram of the actuating duty

In a normal-progress cycle, on the one hand, the states are not-activated (the actuating duty is not available), activated (the actuating duty is being configured), operated (a composed state where the actuating is taking place in terms of receiving and processing data), done (the actuating is complete), and interrupted (the actuating is put on-hold and then resumed). On the other hand, the transitions connecting these states together are activation, sending, start, interruption, resumption, and completion.

Vulnerability's side effects correspond to 3 states, namely, activated (the actuating duty is being misconfigured), processed (the actuating operates differently), and interrupted (the actuating is put

[3] We adjust the sensing behavior reported in [33].

on-hold indefinitely), and 2 transitions, namely, misconfiguration and condition-unmet. We associate misconfiguring actuating with 1 vulnerability, i.e., change in actuating frequency (V_4^a); we associate operating differently of the actuating duty with 1 vulnerability, i.e., altering received input (V_5^a); and we associate indefinite on-hold with 1 vulnerability, i.e., the infinite suspension of actuating (V_6^a).

Communicating. Like sensing and actuating, Figure 6 shows the normal-progress cycle of the communicating duty (plain lines in Figure 6) and the side effects of vulnerabilities that this duty could be subject to (dashed lines in Figure 6).

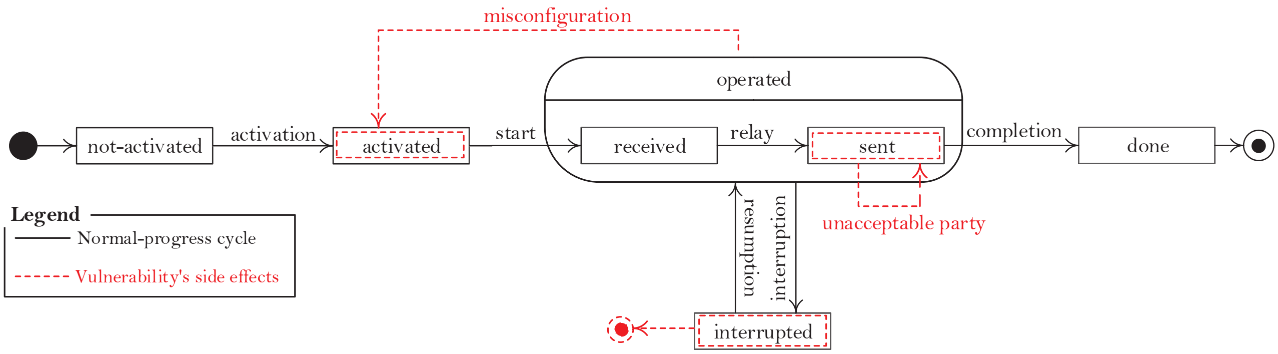


Figure 6: Enriched state diagram of the communicating duty

In a normal-progress cycle, on the one hand, the states are not-activated (the communicating duty is not available), activated (the communicating duty is being configured), operated (a composed state where the communicating is taking place in terms of receiving and sending data), done (the communicating is complete), and interrupted (the communicating is put on-hold and then, resumed). On the other hand, the transitions connecting these states together are activation, start, relay, interruption, resumption, and completion.

Vulnerability's side effects correspond to 3 states, namely, activated (the communicating duty is being misconfigured), sent (the community duty shares data with unauthorized party), and interrupted (the communicating is put on-hold indefinitely), and 2 transitions, namely, misconfiguration and unacceptable-party. We associate misconfiguring communicating with a change in communicating frequency (V_7^c) and a change in communicating protocol (V_8^c); we associate the misuse operation of the thing's duty with a connected unauthorized party (V_9^c); and we associate the indefinite on-hold with the infinite suspension of communicating (V_{10}^c).

4.4.2. *Composite duties*

(Sensing,Actuating). Figure 7 shows the normal-progress cycle of the sensing,actuating composite duty (plain lines in Figure 7) and the side effects of vulnerabilities that this composite duty could be subject to (dashed lines in Figure 7).

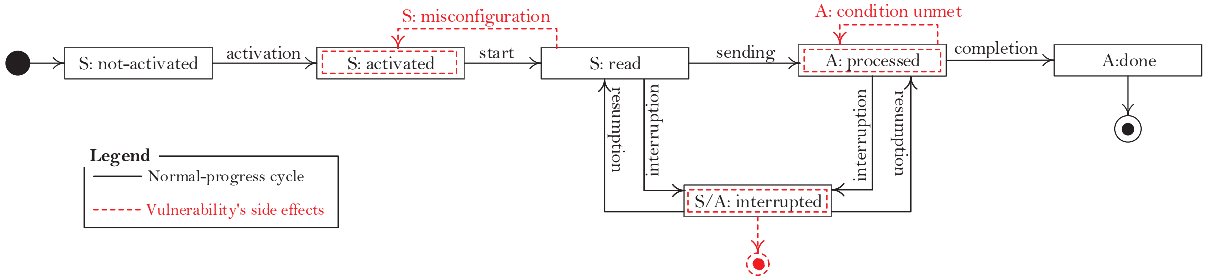


Figure 7: Enriched state diagram of the sensing,actuating composite duty

In a normal-progress cycle, on the one hand, the states are S:not-activated (the sensing duty is not available), S:activated (the sensing duty is being configured), S:read (the sensing duty is taking place in terms of reading), A:processed (the actuating duty takes over from the sensing duty after receiving the sensed data for processing), A:done (the actuating duty is complete), and interrupted (either the sensing duty or the actuating duty is put on-hold and then resumed). On the other hand, the transitions connecting these states together are activation, start, sending, interruption, resumption, and completion.

Vulnerability's side effects correspond to 3 states, namely, S:activated (the sensing duty is misconfigured), S/A: interrupted (either the sensing duty or the actuating duty is put on-hold indefinitely), and A:processed (the actuating operates differently), and 2 transitions, namely, S:misconfiguration and A:condition unmet. We associate misconfiguring sensing with a change in sensing frequency (V_{11}^{SA}); we associate indefinite on-hold with 1 vulnerability, namely, the infinite suspension of sensing or actuating (V_{12}^{SA}); and we associate operating differently of the actuating duty with 1 vulnerability, namely, altering sensed input (V_{13}^{SA}).

(Sensing,Communicating). Figure 8 shows the normal-progress cycle of the sensing,communicating composite duty (plain lines in Figure 8) and the side effects of vulnerabilities that this composite duty could be subject to (dashed lines in Figure 8).

In a normal-progress cycle, on the one hand, the states are S:not-activated (the sensing duty is not

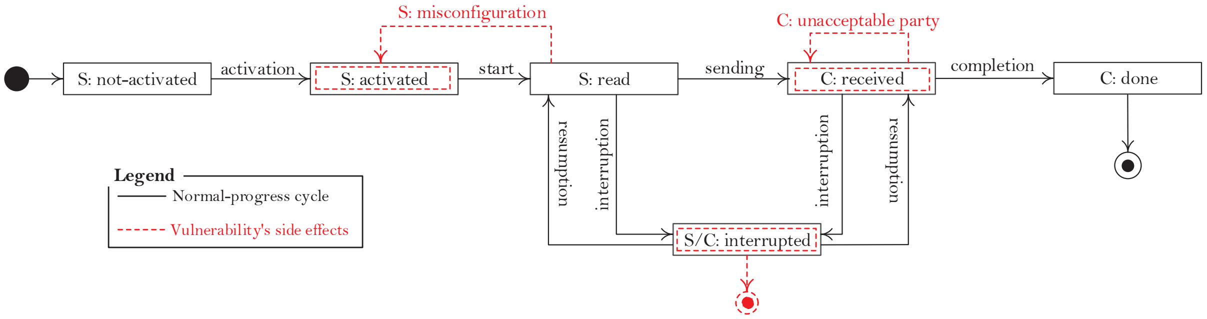


Figure 8: Enriched state diagram of the sensing,communicating composite duty

available), S:activated (the sensing duty is being configured), S:read (the sensing duty is taking place in terms of reading), C:received (the communicating duty is taking place in terms of receiving data), and S/C: interrupted (either the sensing duty or the communicating duty is put on-hold and then, resumed), and C:done (the communicating duty is complete). On the other hand, the transitions connecting these states together are activation, start, sending, interruption, resumption, and completion.

Vulnerability's side effects correspond to 3 states, namely, S:activated (the sensing duty is misconfigured), C:received (the communicating duty shares data with unauthorized party) and S/C:interrupted (either the sensing duty or the communicating duty is put on-hold indefinitely), and 2 transitions, namely, S:misconfiguration and C:unacceptable party. We associate misconfiguring sensing with the change in sensing frequency by an unauthorized person (V_{14}^{SC}); we associate indefinite on-hold with 1 vulnerability, i.e., infinite suspension of sensing or communicating (V_{15}^{SC}); and we associate the misuse operation of the communicating duty with a connected unauthorized party (V_{16}^{SC}).

(Sensing,Communicating,Communicating). Figure 9 shows the normal-progress cycle of the sensing, communicating, communicating composite duty (plain lines in Figure 9) and the side effects of vulnerabilities that this composite duty could be subject to (dashed lines in Figure 9).

In a normal-progress cycle, on the one hand, the states are S:not-activated (the sensing duty is not available), S:activated (the sensing duty is being configured), S:read (the sensing duty is taking place in terms of reading data), C1:received (the actuating duty is taking place in the first thing in terms of receiving data), C1/C2:synchronized (the communicating duty is synchronized between the first and the second things), C2:received (the actuating duty is taking place in the second thing in terms of receiving data), C2:done (the communicating duty is complete) and S/C1/C2:interrupted

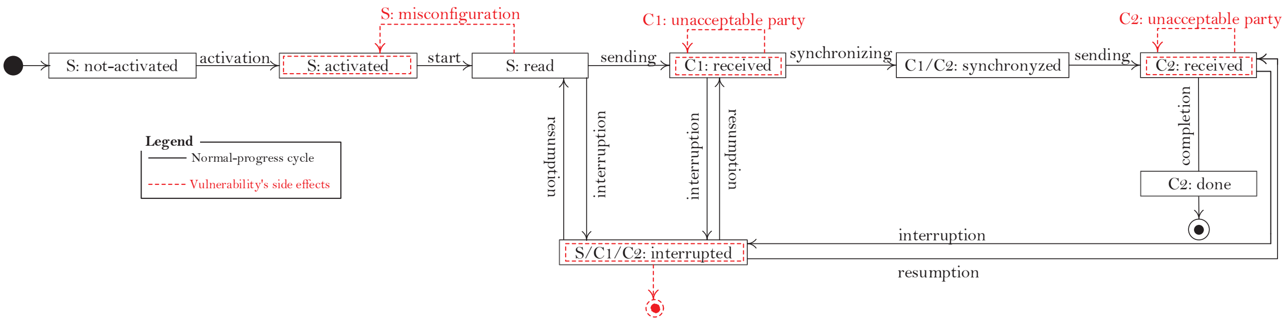


Figure 9: Enriched state diagram of the sensing,communicating,communicating composite duty

(either the sensing duty or the communicating duty in one of the two things is put on-hold and then resumed). On the other hand, the transitions connecting these states together are activation, sending, start, interruption, resumption, relay,and synchronizing.

Vulnerability's side effects correspond to 4 states, namely, S:activated (the sensing duty is misconfigured), C1: received (the communicating duty in the first thing shares data with unauthorized party), C2: received (the communicating duty in the second thing shares data with unauthorized party) and S/C1/C2: interrupted (either the sensing duty or the communicating duty in one of the two things is put on-hold indefinitely), and 3 transitions, namely, S:misconfiguration, C1: unacceptable party and C2: unacceptable party. We associate misconfiguring sensing with the change in sensing or communicating frequency, or resource consumption (V_{22}^{SCC}); we associate an indefinite on-hold with 1 vulnerability, i.e., the infinite suspension of sensing duty or the communicating duty within the sensing duty or the communicating duty in one of the two things (V_{23}^{SCC}), and operating differently of the communicating duty in one of the two things with altering received input (V_{24}^{SCC}).

5. Guiding framework for vetting things

This section presents our proposed $\mathcal{V}$IoT framework (Section. 5.1) and, then, the system that was implemented accordingly (Section. 5.2).

5.1. Architecture

Figure 10 identifies the modules that constitute our framework for vetting things. Vetting ensures that a thing's behavior is in line with its expected behavior (Section 4.4) when tested against vulnerabilities that its duties can be subject to (Section 4.3). The progress of completing the vetting in the framework goes over 5 stopovers.

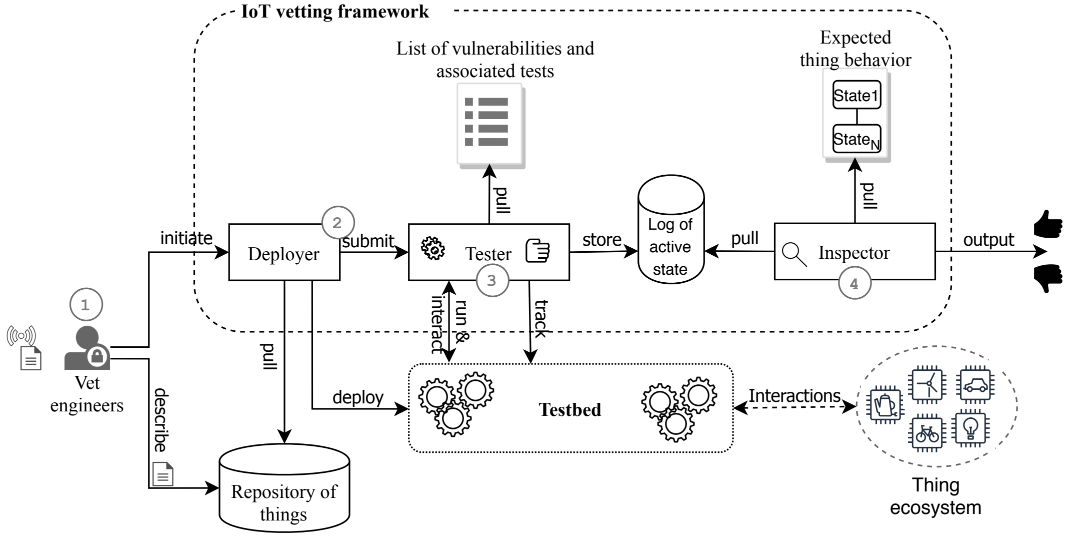


Figure 10: Modules of the $\mathcal{V}$IoT framework

safe

In stopover ①, the vet engineer enriches the description of the thing to vet with details about its atomic/composite duties and then, publishes this description on the repository of things. In stopover ②, the vet engineer deploys the thing on the testbed allowing to run different tests and to support interactions with peers and the Tester module. The deployment is taken care by the deployer module that also extracts the thing's descriptions of duties from the repository of things and submits them to the tester module, thereby initiating the third stopover ③. The tester module (*i*) retrieves the list of known vulnerabilities for the thing based on its duties, (*ii*) selects the necessary tests[4] associated with these vulnerabilities and finally, (*iii*) runs the selected tests. During the tests, the testbed is constantly monitored thanks to the tester module that tracks and stores both the states of the thing and the events in a dedicated log. Upon completing the tests that correspond to stopover ④, the following occurs; the inspector module pulls the behavior of the under-vetting thing from the log and its expected behavior as defined in Section 4.4. Then, it compares the behavior built upon the tests to the expected one: if no vulnerabilities' side-effects are detected then the thing is declared **safe**; otherwise, it is declared **unsafe**.

[4] Tests could be automatic, semi-automatic, or manual.

5.2. *Implementation and experiments*

A system demonstrating the $\mathcal{V}$IoT framework was developed using Python 3, Java 14, JavaScript, MQTTLens [34] and Node-RED [35]. MQTTLens is an add-on for the Chrome browser allowing to publish messages to an MQTT broker, to subscribe to MQTT topics and to receive messages. This latter is a flow-based programming paradigm in which a variety of processes called "nodes" are connected together to form applications called "flows", instead of writing code. Node-RED runs on local workstations, the cloud, and edge devices. It has become an ideal tool for the Raspberry Pi and other low-cost hardware. Node-RED runtime is built on top of Node.js and takes its full advantage in terms of event-driven, non-blocking I/O model. It can be used to build and deploy applications due to its browser-based editor by wiring hardware devices, APIs and online services. Node-RED implements the testbed and includes an MQTT server so that IoT devices could be easily connected via port 1883 using Transport Layer Security (TLS). We considered sensors as things to vet. The vet engineer interacts with the sensors running on the testbed using JSON requests via the deployer module (i.e., MQTTLensTool). The way a sensor was implemented consists of 3 connected objects: living.lights, bed.alarm, and kitchen.aircondition. They were created and deployed by the Node-RED server. On top of Node-RED, other parts (i.e., the tester and the inspector) were implemented using Python language (Spyder Tool V3.7 [36]).

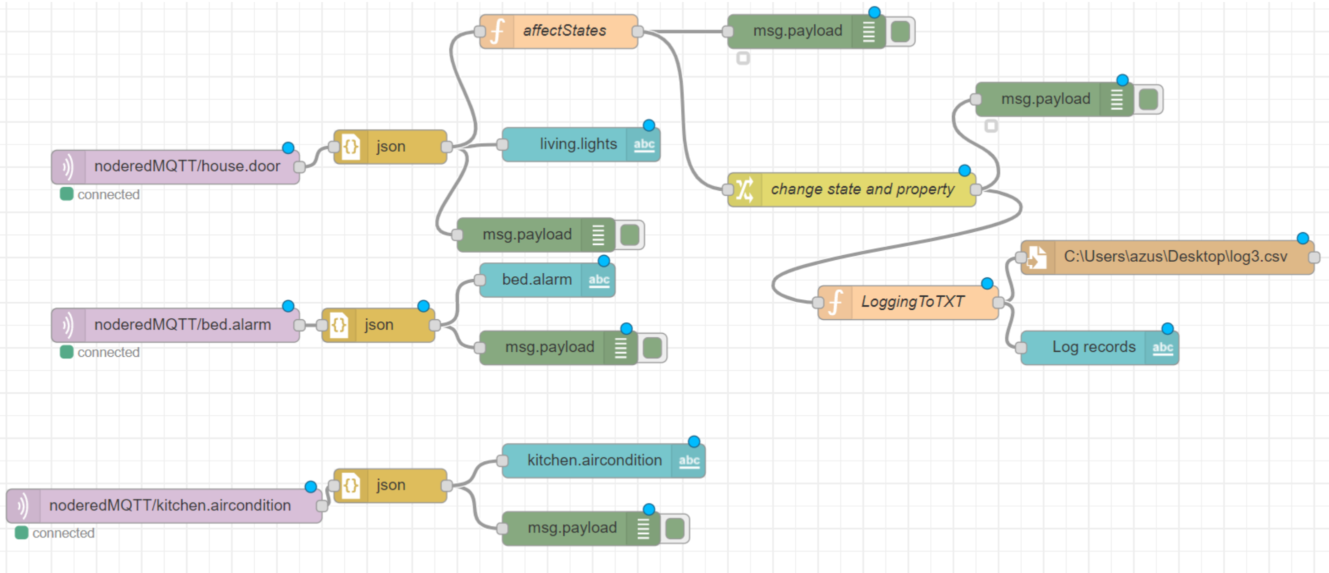
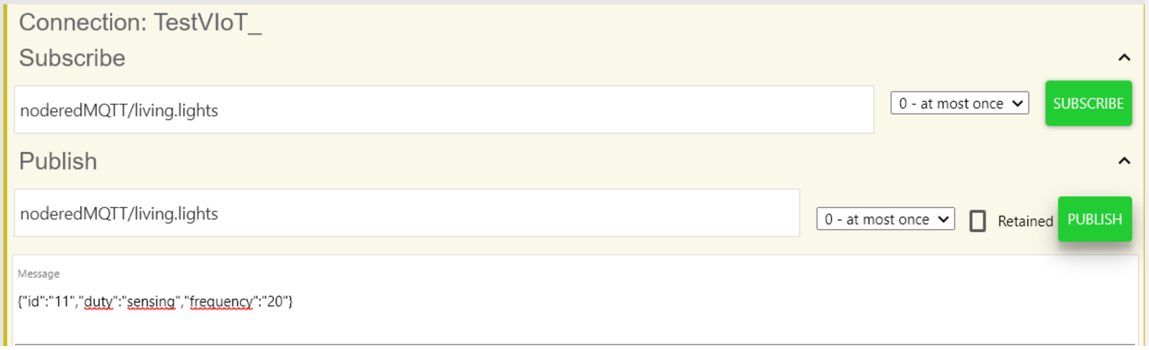


Figure 11: Things deployed in the Node-RED testbed of the $\mathcal{V}$IoT framework

According to Figure 11 (the testbed), we used six node types (*i*) *mqtt input* node allows users to configure an MQTT service and the topic to publish about. As a result, a node could receive messages with the exact same JSON string that was sent via MQTTLens (as shown in Figure 12). (*ii*) *JSON* node which parses messages that MQTT input node generates when it receives an MQTT message and converts it to a JavaScript object. (*iii*) *function* node receives a message object as input and can return 0 or many message objects as output. A message object must have at least a payload property (msg.payload). (*iv*) *debug* node displays the received messages within the flow in the panel. (*v*) *text* node shows messages within the flow on a slider and as a text string. Finally, (*vi*) *change* node changes a message payload or adds new properties. All calls to the testbed's flow are tracked and stored by the Tester in the log of the active states database consisting on a CSV file. Next, the Inspector module compares the stored active states to the expected ones to check the possible existence of any vulnerability.



Connection: TestVIoT_

Subscribe

noderedMQTT/living.lights

0 - at most once

Publish

noderedMQTT/living.lights

0 - at most once

□ Retained

Message

{"id":"11","duty":"sensing","frequency":"20"}

Figure 12: JSON request submission via MQTTLens

To illustrate a vulnerability, we considered sensing duty and set its frequency to every time interval. A vulnerability would consist of communicating differently from the claimed frequency (V_1^s) by using the "change" node. Thus, during the experiment, the Python program related to sensing duty was launched in order to check whether the stored states were as expected. If not, it displayed a notification of a vulnerability. In the following, we considered 2 series of vulnerability-related experiments: vetting duration and vetting efficiency. These experiments run on Windows 10 Asus TUF Gaming i7-8750H @ 2.206Hz, 12Go. Before all, the $\mathcal{V}$IoT engineer sends a JSON request to a living.lights's sensor via MQTTLens Tool as per Figure 12.

1. Vetting duration: to assess the framework's time performance for detecting vulnerabilities. We computed the time of sending a request and the time of detecting a vulnerability. We considered 10 requests with an 2-second time interval between each one, where each request was tampered by changing frequency vulnerability. Then, we recorded the time that the inspector took to process the vetting so, that vulnerabilities were detected. As per Figure 13, we noticed that launching vio-

lations does not affect much the vetting latency since the active states are checked by the Inspector module.

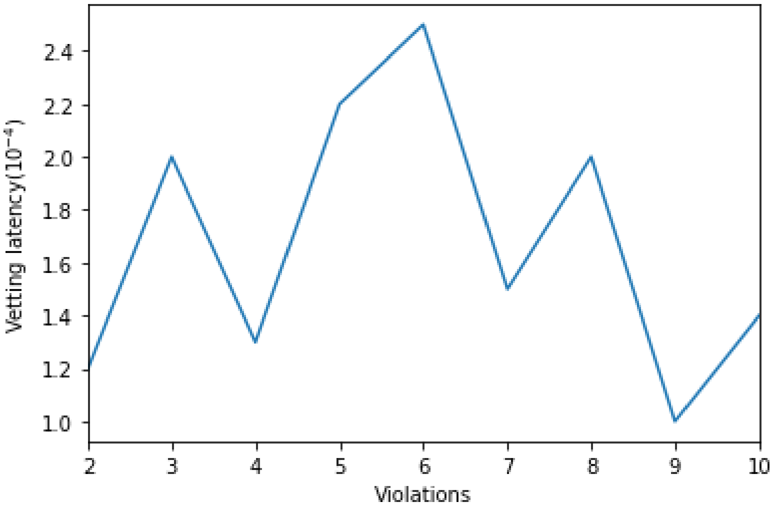


Figure 13: Latency-based $\mathcal{V}$IoT framework performance

2. Vetting efficiency: to assess the framework's capacity to detect vulnerabilities based on precision and recall. The precision expresses the ability of the Inspector module to detect correct (i.e., that actually happened) vulnerabilities only. It is defined by calculating the ratio of the number of true vulnerabilities among the launched vulnerabilities as per Equation (1), where TV is the number of true vulnerabilities, and FV is the number of detected false vulnerabilities.

$$Precision = \frac{TV}{TV + FV} \tag{1}$$

The recall is defined as the ratio of true vulnerabilities over the total number of detected vulnerabilities by the Inspector, as per Equation (2), where FN is the number of missing true vulnerabilities that are not detected. It represents the probability of detecting all true vulnerabilities among the detected vulnerabilities.

$$Recall = \frac{TV}{TV + FN} \tag{2}$$

In these experiments, we relied on the vulnerabilities used in the first series (Figure 13). Then, we observed the behavior of the Inspector module in terms of number of detected true/false vulnerabilities, and the number of non-detected ones to determine the precision and recall values (Table 4).

As per Table 4, we noted that the $\mathcal{V}$IoT framework is efficient by achieving a precision close to 1 in

Table 4: Precision/recall results

Vulnerabilities	1	2	3	4	5	6	7	8	9	10	Total
TV	1	1	0	1	1	1	1	1	1	1	9
FV	0	1	0	1	2	0	0	0	0	0	4
FN	0	0	1	0	0	0	0	0	0	0	1
Precision	1	0.5	0	0.5	0.33	1	1	1	1	1	0.9
Recall	1	1	0	1	1	1	1	1	1	1	0.9

most of vulnerabilities (same for recall values). We also noticed that there is only one missing vulnerability among 10 (the third vulnerability). The efficiency of the VIoT framework in terms of precision/recall is explained by the presence of the inspector that browses instantly the active states of the connected things, where each is checked separately wether it is as expected or not.

6. Conclusion

This paper discussed the importance of vetting things prior to their integration into systems, some of which are critical. The objective is to verify claims of providers about the safety of things as some could be subject to vulnerabilities that could be taken advantage of for non-beneficial practices. The IoT paradigm imposes a new way of how determining security, confidentiality, identity, and privacy should be approached. By analogy to mobile apps vetting, we identified the vulnerabilities that could impede things' duties from successful completion and then illustrated how these vulnerabilities could be detected. The duties are referred to as sensing, actuating, and communicating; they have been examined separately in the context of atomic duties and then combined, in the context of composite duties. The outcome of vetting either ensures thing's trustworthiness when their behaviors meet the expected execution cycles or declares them as unsafe. Future work will target completing the testbed by vetting more things and more duties, whether atomic and composite, and examining the concept of provable vetting so that things would be accountable for the duties they perform.

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