

Looking for a Black Cat in a Dark Room: Security Visualization for Cyber-Physical System Design and Analysis

Georgios Bakirtzis*

Brandon J. Simon†

Cody H. Fleming‡

Carl R. Elks§

ABSTRACT

Today, there is a plethora of software security tools employing visualizations that enable the creation of useful and effective interactive security analyst dashboards. Such dashboards can assist the analyst to understand the data at hand and, consequently, to conceive more targeted preemption and mitigation security strategies. Despite the recent advances, model-based security analysis is lacking tools that employ effective dashboards—to manage potential attack vectors, system components, and requirements. This problem is further exacerbated because model-based security analysis produces significantly larger result spaces than security analysis applied to realized systems—where platform specific information, software versions, and system element dependencies are known. Therefore, there is a need to manage the analysis complexity in model-based security through better visualization techniques. Towards that goal, we propose an interactive security analysis dashboard that provides different views largely centered around the system, its requirements, and its associated attack vector space. This tool makes it possible to start analysis earlier in the system lifecycle. We apply this tool in a significant area of engineering design—the design of cyber-physical systems—where security violations can lead to safety hazards.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Graph drawings; Human-centered computing—Visualization—Visualization systems and tools—Visualization toolkits; Security and privacy—Systems Security—Vulnerability management; Security and privacy—Security in hardware—Embedded systems security

1 INTRODUCTION

Security visualizations have changed the way we view, organize, and respond to system violations. The study of effective visualizations for security has led to better mitigation strategies applied in real time [28]. Nevertheless, there are two areas where visualization has made little progress: assessing the security posture of competing design patterns early in the system’s lifecycle and effective visualization for large amounts of evidence generated at the early design phase.

This issue was not as critical when systems took years to develop and deploy—where designs went through several rounds of testing, specifications were clearly defined, and a main architect took responsibility for the development of the system. Recently, however, there has been a shift to deploying system’s designed using commercial-off-the-shelf (COTS) hardware on top of open-source software, which has the *potential* of reducing technical debt and

financial cost. On top of this, non-safety-critical and safety-critical systems alike are increasingly connected to the internet. (See, for example, the security and privacy issues surrounding the industrial internet of things [31].)

For this reason, a significant challenge is the secure design and deployment of cyber-physical systems (CPS), where security violations can lead to unsafe physical behavior [29]. Effective visualizations in this area would achieve a higher degree of operational assurance with respect to security in applications where security violations could lead to safety hazards, such as medical systems [9], aviation [1], automotive [19, 20, 24] and electric power [25], to name a few.

Furthermore, the use of systematic and standardized analysis through effective visualization in the CPS domain provides a common language between security professionals and system designers, which is currently limited. The lack of such language in the security domain can have detrimental effects, including miscommunication of security requirements to system designers, security applied for the sake of security (not based on real operational needs), and security obstructing system requirements.

Additionally, a major problem in applying security as a lifecycle practice is that the amount of data generated at the design phase is significantly larger than that used for the analysis of realized systems. This is because, the inherent incompleteness of information at the design phase produces a large amount of applicable attack vectors. Lacking information includes but is not limited to the specific versions of software, the security patches that will be applied to the system, and the potential insecurity caused by the coupled system.

Moreover, security data is recorded to be parsed and used by security professionals. Security analysts are expected to be looking for specific vulnerabilities and attack patterns to report in a standardized fashion—making implicit assumptions and using expert knowledge from previous experiences. The current challenge is to allow system designers to use security data. This is one way that system security can be exercised as a lifecycle practice; especially earlier in the lifecycle where decision effectiveness is highest [22, 32, 35].

To combat these challenges, we implement a security analyst dashboard that can be used preemptively from the early stages of a system’s lifecycle to deployment and operation, where resilience or hardening defenses might be added.

Contributions. The contributions of this work are:

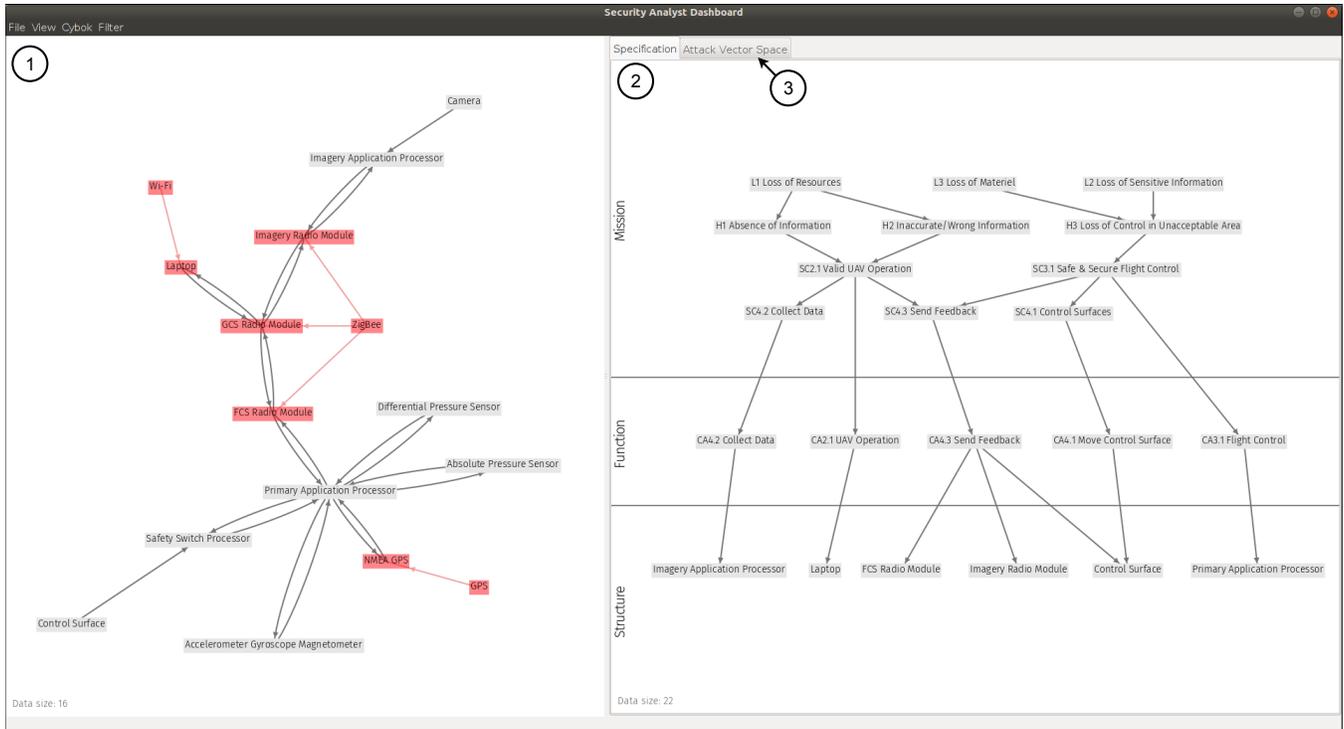
- We develop an open-source security analyst dashboard that supports system designers and security analysts alike; in turn, this provides a common language between the two.
- We provide important functionality to deal with the large number of data intrinsically produced when applying security analysis in the absence of a realized system.
- We present system and operational information lacking from current security analysis and visualization tools that define the mission of the system and, consequently, allow tracing potential security violations to degradation of mission-level requirements.

*Electrical & Computer Engineering, Virginia Commonwealth University, Richmond, VA, USA (email: bakirtzisg@ieee.org)

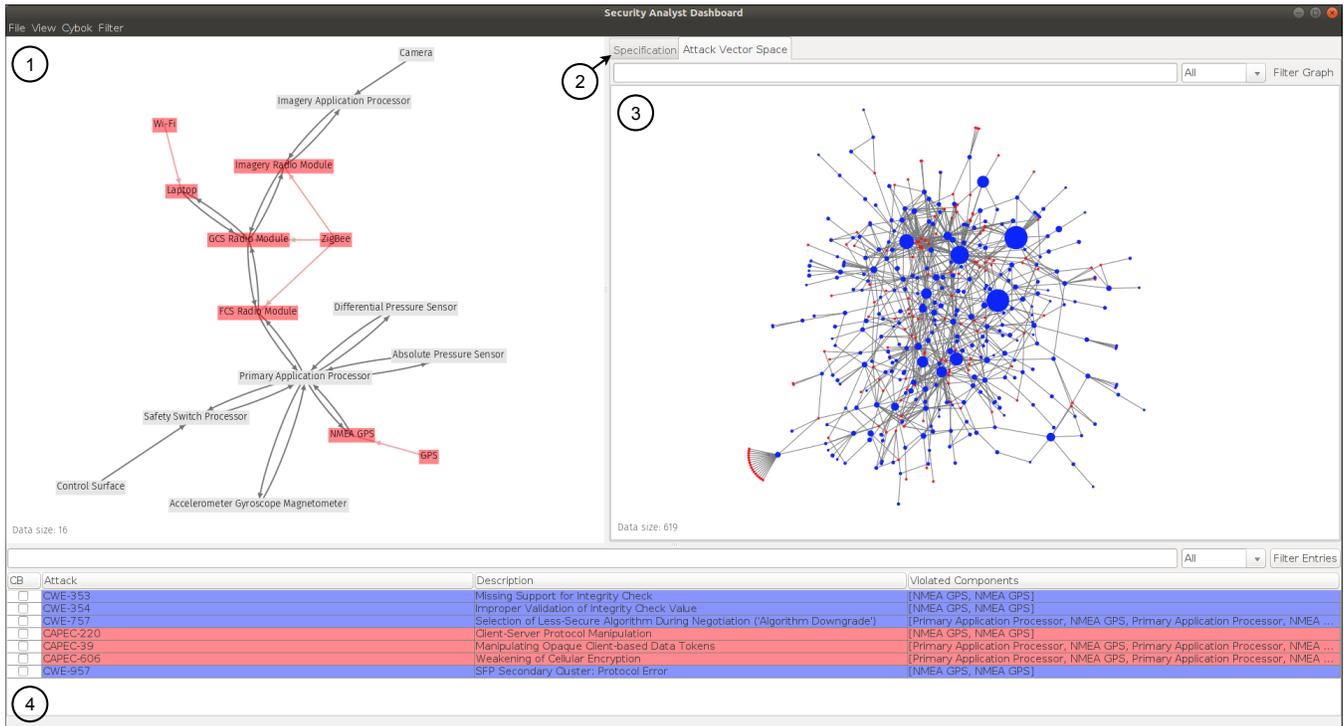
†Electrical & Computer Engineering, Virginia Commonwealth University, Richmond, VA, USA (email: simonbj@vcu.edu)

‡Systems Engineering and Mechanical & Aerospace Engineering, University of Virginia, Charlottesville, VA, USA (email: fleming@virginia.edu)

§Electrical & Computer Engineering, Virginia Commonwealth University, Richmond, VA, USA (email: crelks@vcu.edu)



(a)



(b)

Figure 1: Screenshots of the user interface of the proposed security dashboard. The dashboard supports diverse information for better informing system designers and security analysts alike of the goals of the system (specification), the potential attack vectors that can violate the goals of the system, and the system attack surface projected over the system topology.

2 SECURITY ANALYST DASHBOARD

2.1 Domain problem

In the design of complex systems in general—but specifically in the area of CPS design and analysis—it is important to consolidate information from a diverse set of stakeholders. These include but are not limited to the operations staff, end users, and subject domain experts. System designers and security analysts need to consider all this information when proposing a possible design solution. Furthermore, it is becoming increasingly evident that system designers and security analysts require a common language, such that security considerations are applied proactively during system design and throughout the system’s lifecycle.

By definition, the amount of information to consider at the design phase is significantly larger and more complex to navigate compared to the security analysis of a realized system. This problem is further extended in CPS by the need to avoid hazardous and unsafe behavior. In addition to potential system violations; that is, exploitation of system resources, system designers and security analysts need to be aware of the requirements, for example, unacceptable losses, potential hazards, unsafe control actions, and admissible functions of the system.

To overcome these challenges we propose to collectively analyze both safety and traditional attack vector artifacts based on a system topology model, which allows the analyst to provide a thorough and complete security report. To achieve this effectively, the dashboard presents and allows for navigating the large number of informational artifacts generated at the design phase through several graphs. The two primary means of analysis conducted using the dashboard are:

- **Systems-theoretic analysis (top-to-bottom)** Security violations are emergent properties of the system. Emergent properties stem from the coupling of subsystems and cannot be investigated by examining the subsystems individually. This means that the assessment of individual elements of the whole system is insufficient to assure safe and secure behavior. Furthermore, security needs to be exercised to the extent necessary based on the system’s expected service [15]. Therefore, this analysis relies on data collected through a structured elicitation process [17] and is captured in Systems Modeling Language (SysML) [18]; a familiar and often used modeling language to Systems Engineers. The model is then transformed automatically to a graph using GraphML [13, 16]. The purpose of using a GraphML metamodel is to allow agnosticism towards modeling tool or language. The resulting artifacts allow system and security analysts to reason about defenses and potential violations in a system’s design without requiring a prototype realization for testing potential hypothesis on. This, in turn, allows for quick comparisons of potential designs with respect to their security posture. While this information is a natural consequence of good systems engineering, it is often omitted from security analysis. Consequently, security is applied in a reactive *bolt-on* fashion instead of being applied proactively—at the early stages of system design—and reapplied and assessed thereafter—up to deployment and operation. By consolidating this information in a security analyst dashboard we present the systems and its operational goals as equally important to traditional attack vector analysis.
- **Attack vector analysis (bottom-to-top)** Following the top-to-bottom analysis there is a crucial stage, where traditional vulnerability analysis is applied in a model-based setting. By exploring and filtering the attack vector space it is possible to construct a defensible evidential trace of potential violations in the system. This is possible by adding extra design information in the system model that can map to historically recorded attack vectors [12]. To do this automatically we use techniques from

computational linguistics in conjunction with the exported GraphML models [11]. This analysis complements the top-to-bottom analysis with real attack vectors, *evidence*, in the absence of a realized system. By doing so, we are able to reduce the criticality of elements that might seem crucial using only systems-theoretic means but are unlikely to be successfully violated. We note, that this approach could be extended to private repositories of companies or agencies to extend the amount of known attack vectors.

2.2 System & specification models

As systems become more complex, how does one know what security needs exist (e.g., what should or should not be secured) if one does not know what the system needs to do (or must not do)? Visualization can help answer this question, but this begs a further question: what must be visualized? One answer comes from the principles of systems engineering, which attempts to design and manage complex systems through the development of system requirements, understanding how the system should behave functionally, and creating an interacting set of components (i.e., an architecture) that achieves these behaviors. In the context of security, one must define what the system *should not do*, in addition to requirements capturing what the system *should do*.

Taken together, these artifacts—(1) system requirements, (2) functional behavior, and (3) architecture—result in a specification. This specification then forms the intellectual basis for visualization; that is, what should be visualized and why. For example, an analyst investigating a particular component might be able to visualize the components it interacts with (via the architecture), the kinds of behaviors these components give rise to (via the functional diagrams), and ultimately the expected service that the component is critical to (via the requirements).

This is especially important in assessing the security posture of CPS, because of the tight integration of digital control with the physical environment. The specification should capture what impact can result from the violation of digital components and how that impact is reflected in the physical world.

Therefore, the model includes all important attributes that are necessary for a holistic consequential security analysis. That is, it includes the specification, the admissible behaviors, and the system topology that implements the admissible behaviors. To use the model with the dashboard we transform the SysML definitions of the requirement diagrams and internal block diagrams to graphs. The system topology graph is transformed to a directed graph $\Sigma = (V, E)$, where the vertices, $V(\Sigma)$, are the assets of the embedded CPS and the edges, E , a dependence relationship between system assets (Figure 1 ①). The specification is transformed to a directed hierarchical constrained layout graph, $S = (V, E)$, such that the different levels are independent and $V(S)$ the unacceptable losses, potential hazards, safety constraints, and critical components of the system topology graph, Σ (Figure 1a ②).

Normally, such a specification is captured in tables. However, to fully leverage the specification the analyst should be able to immediately see the relationships that exist between different types of information. This is especially the case when the analyst wants to examine the impact of either a specific attack vector applicable to critical system elements or when assuming that element will be violated, based on the analyst’s previous experience.

2.3 Attack vector datasets

In addition to the construction of models for describing the requirements, functions, and topology of the system we use open datasets to describe attack patterns, weaknesses, and vulnerabilities. These datasets have the additional benefit of having a hierarchical taxonomy. Specifically, the datasets used by the security dashboard are MITRE Common Attack Pattern Enumeration and Classification

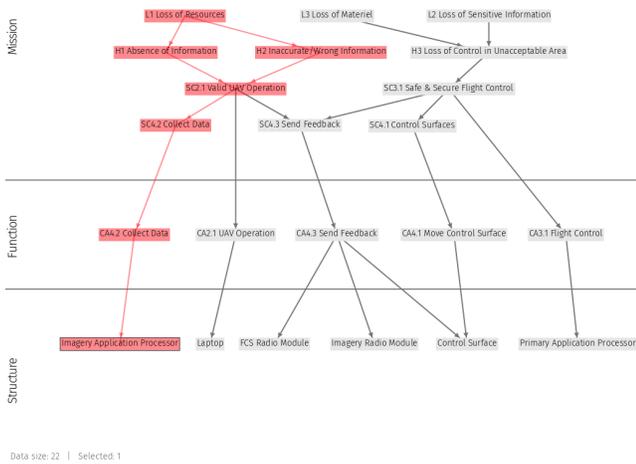


Figure 2: Screenshot of the dashboard showing the completed mission specification, including a chain of violations in the event that the *Imagery Application Processor* is violated through an attack vector.

(CAPEC) [2], MITRE Common Weakness Enumeration (CWE) [4], and NIST National Vulnerability Database (NVD) [7], which recently took control of MITRE Common Vulnerabilities and Exposures (CVE) [3].

In general, attack patterns associate with weaknesses and vulnerabilities can abstract to weakness classes. Given this intrinsic relationship between the databases it is possible to represent the attack vector space as a combined undirected attack vector graph $AV = (V, E)$, where $V(AV)$ the total collection of entries of the datasets and E the intra-related edges within each dataset and inter-related edges between dataset entries (Figure 1b ③). This provides an intuitive basis for exploring, filtering, and categorizing entries visually.

A significant concern in visualizing these datasets as a graph is the number of entries in each dataset. To date, there are approximately one hundred and fourteen thousand entries in total, most of which are from NVD. Therefore, even though NVD is extensive and required to be thorough with the analysis at the fidelity of the model, most of them can be abstracted to classes of weaknesses as defined in CWE. By utilizing this abstraction the number of total entries is reduced to the size of the CAPEC and CWE datasets (around twelve hundred all together). Therefore, at the worst-case scenario the starting attack vector graph the analyst has to consider is significantly smaller but equivalently descriptive without including all CVE entries.

Whilst a graph of this size can become overly complex and difficult to navigate, it is a natural design choice for the attack vector space associated with a system. This is because a graph representation precisely captures the *neighborhoods* of attack vectors related to the system. To manage this complexity we add intuitive interactivity and filtering functionality such that the analyst can quickly narrow down the results to what is relevant (Section 2.4).

Additionally, by using this data, the analyst supplements a speculative *what-if* analysis with specific pieces of evidence that such violations are possible in the system. This information can then be used to inform the rest of the stakeholders to decide further applicable defensive requirements.

2.4 Visualization & interaction design

Compared to real-time monitoring visualization tools, dashboards used for in-depth analysis require a sophisticated set of interactivity functions to facilitate effective exploration of diverse types of data [23]. For example, by examining the system topology the analyst is also informed about either the specification or the attack

vector space. This makes the individual data dynamic with respect to each other and not just static complementary views.

Towards that goal, the main frame of the security analyst dashboard organizes the information in three main panes:

- **System topology (Σ).** The system topology graph is a visualization of the design under analysis. It also contains security specific information, including the attack surface of the system [27]; that is, the elements that a potential intruder can enter from based on found recorded historic attacks at the entry point of the element (indicated by red vertices). Additionally, given a specific element to violate, we draw the path of the potential exploit chains that can lead to its violation; that is, all paths from any element of the attack surface to the chosen element, where attack vectors have been found for the full path—both for the vertices and edges in that path—which is indicated by yellow vertices and edges (Figure 3 ①). Using this visualization the analyst can gather insights about the security posture of the system without having to investigate individual attack vectors. Simply by using visual cues it is possible to gain quick ideas about where and how to add defenses or apply resilience techniques.

- **Specification (S).** The specification graph provides a view to the expected service from the position of its requirements; that is, reiterated from before, the unacceptable losses, the potential hazards the system might have during deployment and operation, and the safety constraints, which define its overall mission, its control actions, the functionality necessary to achieve its mission, and finally, the critical system elements that in the case of violation will lead to the violation of other necessary system functions.

The layout of the graph is custom; it defines constraint intervals based on the category of the vertices: (1) the mission-level requirements, (2) the functional requirements, and (3) the elements of the system topology structure that are part of the specification. By doing so, it shows the specification as a natural visual hierarchy, with the mission at the top, the function in the middle, and the structure at the bottom. An important action available in the specification graph is seeing at any level what violations happen above or below it. For example, an analyst can click on a structural element and see what functions and mission requirements are also violated, which allows him to understand the degree of mission degradation that occurs in that instance (Figure 2).

- **Attack vector space (AV).** The attack vector graph shows all the attack vectors that could potentially violate any given component in the system topology. Moreover, this graph visualizes the inter-related and intra-related connections that are intrinsic between the vertices because of the hierarchical nature of the datasets; that is, CAPEC, indicated in red, and CWE, indicated in blue. The entries of CVE are abstracted to their corresponding CWE classification. This achieves a significantly lower number of vertices to visualize and explore with no significant loss of information. Right-clicking on a given vertex that has consumed CVE vertices will give the option to reveal the nearest neighbors, including the specific CVE entries, indicated in yellow. Additionally, to indicate how important a given CWE entry in the attack vector space is the sizing is controlled by how many CVE entries it has consumed. The attack vectors are matched automatically using another tool that also produces GraphML files [11], which implements a search algorithm to determine which attack vectors could be relevant to the system topology. The vertex positioning is based on the Fruchterman-Reingold force layout algorithm. It follows, that the graph layout produces clusters of similar attack vectors

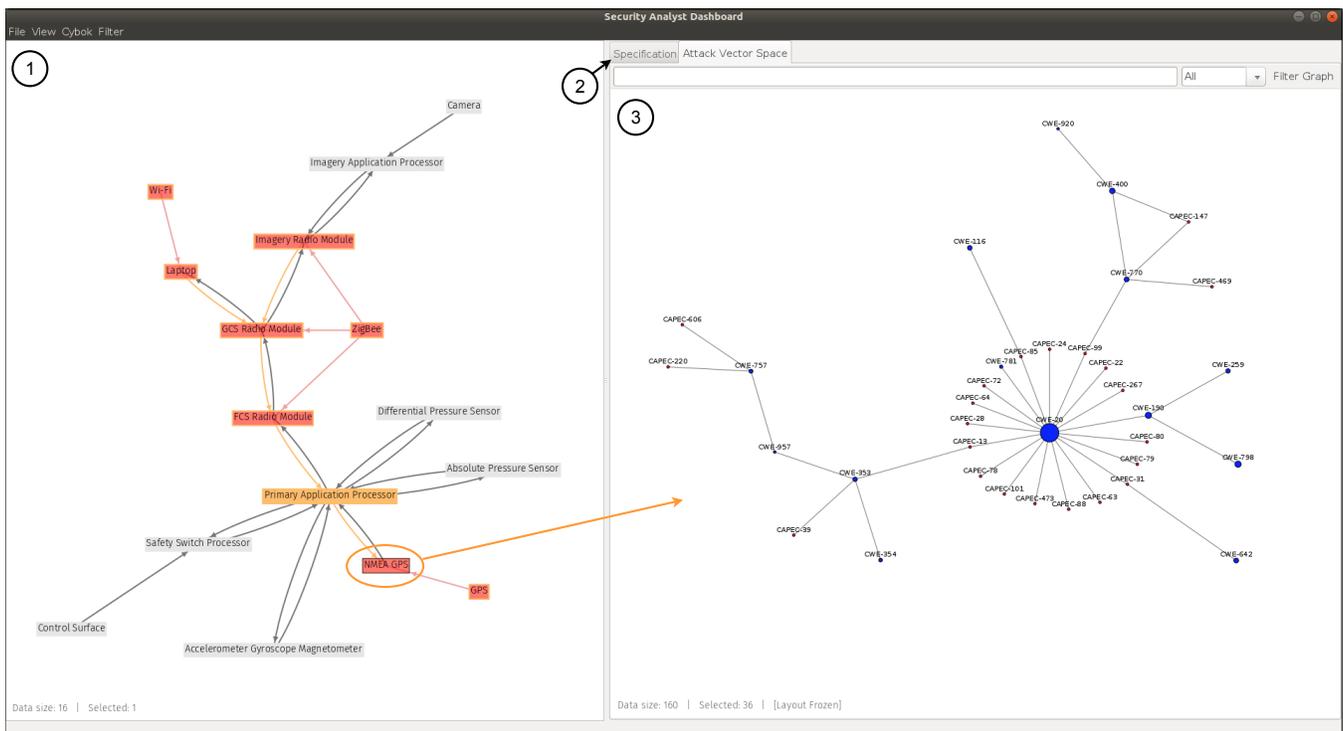


Figure 3: Screenshot of the dashboard showing exploit chains in the system topology graph (①) and filtering of the attack vector space per component; in this case NMEA GPS (③), which allows the user to produce reportable evidence of potential violation in the system topology.

and, therefore, whole clusters can either be further examined by zooming in or completely removed (Figure 1b ③). Finally, the analyst can double-click on the attack vertices to see all further information in a pop-up window if needed.

All three main panes share actions; that is, most interactive functions present in the dashboard project to the other panes. For example, clicking on a vertex in the structure of the specification, selects the same element in the system topology graph and filters the attack vector space only for the attack vectors applicable to that vertex.

An extra but equally important pane in the security analyst dashboard is the *bucket* (Figure 1b ④). The bucket is used as a collection of attack vectors that the analyst wants to further investigate over the system topology or report to the stakeholders.

Specifically, the bucket contains a table where each row is an attack vector containing the attack name, a description, and what component(s) it potentially violates. The rows are color coded the same way as the attack vector graph to allow for visually identifying between datasets. The bucket is an essential part of the dashboard as it allows for the analyst to collect attack vectors based on experience and, therefore, preemption and mitigation have to be considered by the stakeholders. As an additional feature, the attack vectors in the bucket can be selected and projected in the system topology; that is, constructs the edges to the components the attack vector can violate. This feature can provide further insight; for example, the analyst might have chosen the attack vector from filtering based on a specific component but when projecting it to the system topology finds that it can also violate several other components (Figure 4).

2.4.1 Data filtering

When dealing with a large amount of data—as is the case with the attack vector graph, AV—it is important to implement effective filtering techniques. To that end, there are several options for filtering

data, the most direct of which is using filter bars. In the security analyst dashboard there are two filter bars: one located within the attack vector graph pane (Figure 2 ②) and one located within the bucket pane (Figure 1b ④). Options to filter include the attack database identification number, name, description, by the components in which it violates, or all of the above. Additionally, the search criteria supports regular expressions (RegEx) to filter attack vectors efficiently. The filter bar also implements the option to show only the attack vectors visible in the bucket; that is, all attack vectors that the analyst has deemed important for further evaluation.

The system topology graph can also be used to quickly filter the attack vectors by a specific system topology element vertex or a set of vertices (Figure 3 ① & ③). This way, the analyst can utilize the three main panes, by examining the criticality from the systems-theoretic analysis and then producing evidence to support that the violation has recorded attack vectors. The analyst can then sort through and explore that space normally, since the number of attacks to consider is significantly lower. Finally, the analyst can choose potential attacks to add to the bucket as reportable artifacts to system designers and other stakeholders.

2.4.2 Model & artifact manipulation

While the model is predominantly constructed by Systems Engineers, it is useful for analysts to be able to manipulate the model's attributes, such that they can constrict the attack vector space. This is because the attributes of the system topology model define the fidelity of the model itself with respect to the corresponding attack vector space. Indeed, changing the attributes of the model is equivalent to changing the system design itself. Such minor changes can either show further recorded historic attacks or, on the other end of the spectrum, reduce the amount of attacks. Clearly, this mechanism can be used for quick *checkups* that can then be changed in the model itself or discussed with the system designers as viable alternatives to the current design of the system topology. An example of such

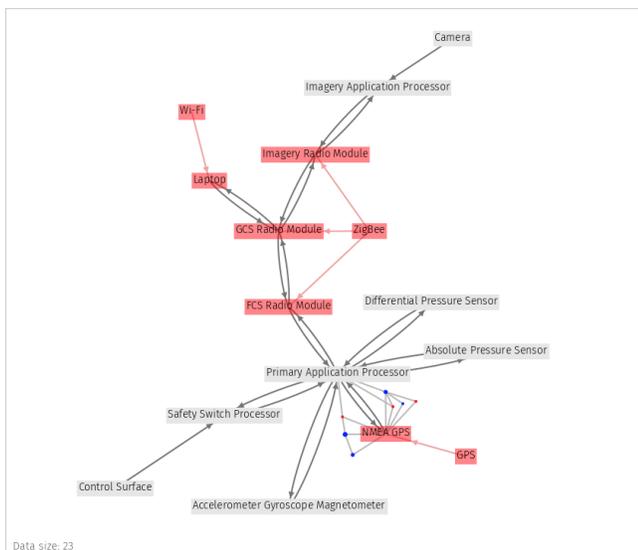


Figure 4: Screenshot of the dashboard showing the projection of a selected number of attacks vectors from the bucket. Hovering over the attack vector nodes or zooming further in reveals further information.

action could be the change from one specific instance of a sensor to another. This presumes that a sensor with a smaller attack vector space is more secure than one with a larger attack vector space.

However, being informed about the general attack vector on the class of the sensor, for example, GPS, is also important. Attack vectors applicable to a specific GPS that do not match with a different GPS implementation might still be viable. Model-based security analysis is an iterative learning experience, allowing circumspection about how a system might (mis)behave in response to different attack vectors. Through this mechanism we attempt to bring *what-ifs* into security analysis.

An additional action important to an analyst is to manipulate the attack vector space directly—through interactive functions like deleting or potentially adding vertices to the attack vector space—to include information from personal domain-expert experience. This is because, given the model-based setting, the search results may contain attack vectors that do not necessarily apply to the system. For example, certain attributes might produce weaknesses related to Embedded Java, but the analyst knows that no software on board the CPS will run Embedded Java. In this case, it is useful for the analyst to remove such vertices from the attack vector graph. For that reason, the dashboard implements the ability to delete any number of attack vectors by selecting them directly from the graph.

2.5 Replication

To allow replication of our results a version of the current implementation associated with this paper is hosted on GitHub, including all helper tools to extract and construct the data requirements in use in the security analyst dashboard [14]. The dashboard utilizes the Java 8 language framework to allow for crossplatform operation of the Graphical User Interface (GUI). To create and render the data as graphs we use GraphStream 1.3 [21].

3 EXAMPLE ANALYSIS

The security analyst dashboard is a natural progression to model-based security assessment. Before, we used several other visualization and data management tools to varying degrees of success. None of them could by default provide a single view on the data requirements imposed by model-based security analysis. Currently

the security analyst dashboard is in use as a research tool to evaluate different techniques for safety and security in CPS. A use case study with domain experts would strengthen the results present in this section. Unfortunately, this is not currently possible because we have had difficulty finding interested individuals with such narrow domain expertise. For this reason, this section presents several workflows that we as researchers found illustrative in sorting through the data necessary for a holistic assessment of the system’s security posture.

Specifically, to evaluate the security analyst dashboard we use a model of a UAS, its mission specification, and its associated attack vector space. Through its attack vector space we also use the notion of exploit chain and attack surface projected over the system topology model.

3.1 Systems-theoretic analysis

Emma, a Systems Engineer, is tasked with designing a CPS using COTS hardware and custom software. As part of the design process she has constructed a system specification and modeled a system topology. Additionally, she has run the attack vector analysis tool and exported all artifacts to use in the dashboard (Figure 1a). Emma immediately notices two things. First, that all radio modules are part of the attack surface—colored in red—and also observes that all radio modules share the same violated attribute; that is, ZigBee (Figure 1a ①). Second, she notices that the imagery radio module is part of the system specification, meaning that it is a critical part of the system. Before even starting to use the tool Emma is already significantly more informed than by just looking at the SysML model through the visualizations of the information produced by the security tool.

Emma clicks on the “Imagery Radio Module” vertex on the system specification and immediately notices that if it is violated it would cause all three unacceptable losses (L1, L2, & L3) through the colored paths from the vertex to the function; that is, “CA4.3 Send Feedback,” all the way up to a subset of safety constraints and all hazards (H1, H2, & H3).

Emma decides to report this to other stakeholders, including other security analysts on the team and Systems Engineers about the possibility of adding defenses if applicable or considering other resilience mitigation options.

She similarly explores the rest of the interactions and brings to attention problematic areas based on her expertise. If the solution is easy she can change the attributes of the system model to further check if the space changes, for example, instead of using XBee which requires the ZigBee protocol, she chooses a different radio module, which does not produce any attack vectors and therefore would not be part of the attack surface or she might decide to make the system redundant and add multiple different types of radio modules in the event that other radio modules are equally vulnerable. By doing so, she builds a strong case for changing the current system topology design that she can report to the rest of the stakeholders.

3.2 Attack vector analysis

Garrett, a security analyst, is not familiar with safety methodologies. He is, however, intimately familiar with attack vectors; that is, attack patterns, weaknesses, and vulnerabilities and has extensive experience in embedded CPS design and implementation. In fact, Garrett has designed and implemented a UAS before, but had not been aware of the specific operational goals of the system.

Through that experience Garrett knows that if the “Primary Application Processor” is violated there would be full mission degradation. Since Emma has already brought to his attention the potential impact of the radio module, he combines the two and examines the possible exploit chains that the security tool has produced for the “Primary Application Processor”. By doing so, he quickly finds out that there are several paths from all radio modules, including the dreaded

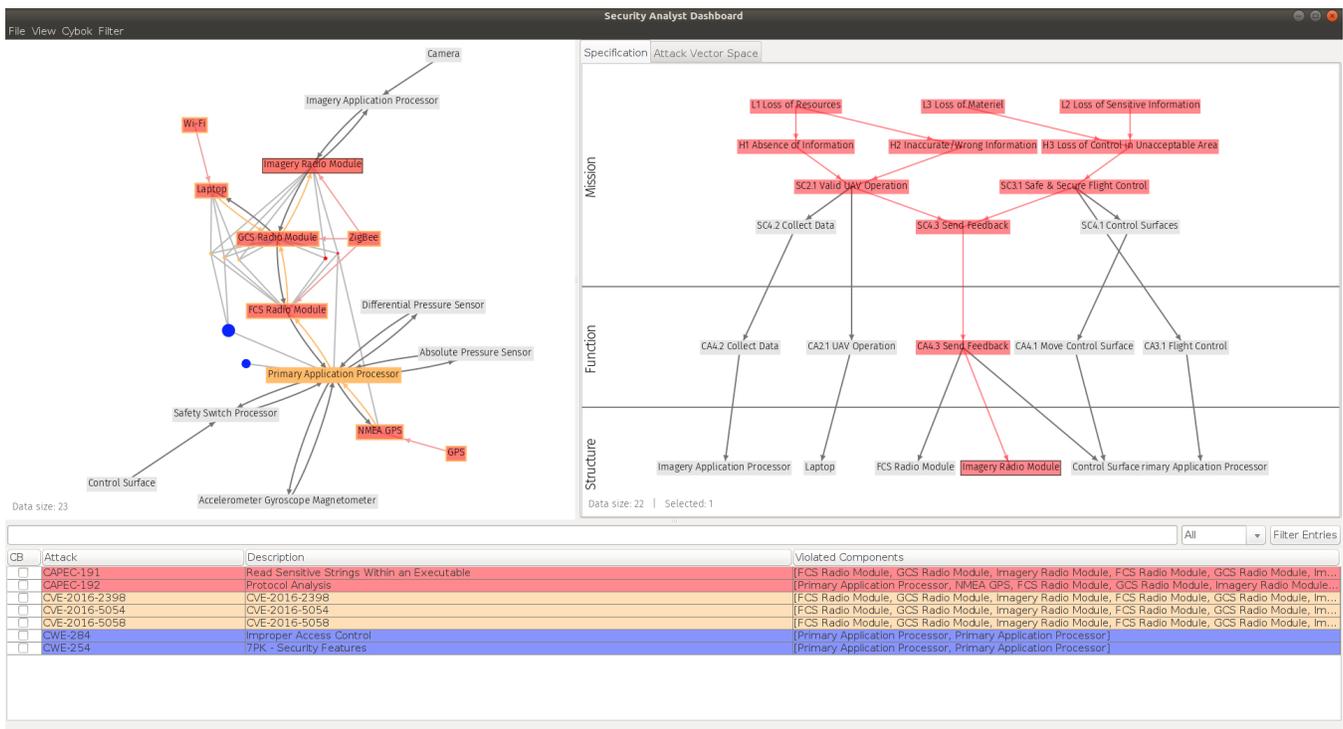


Figure 5: Screenshot of the dashboard showing the completed analysis by both a Systems Engineer and security analyst.

“Imagery Radio Module” to the “Primary Application Processor” (Figure 3 ①).

Garrett is now significantly more concerned than before about the possibility that if the radio modules are violated a clear and direct path is possible both through the vertices and the protocols defining the edges. He is not so much worried about the “NMEA GPS,” from previous experience and he already has designed hardening techniques for the Wi-Fi module in the laptop.

Garrett wants to filter down to the attack vectors applicable to the “Imagery Radio Module”, he changes to the attack vector space pane and double-clicks on the “Imagery Radio Module” on the system topology pane. He immediately sees the hundreds of attacks get filtered down to only the relevant ones. He zooms in to see the names of the attacks without hovering. He further searches and double-clicks on CVE entries to see the neighbors and the specific CVE entries. With a few further searches in the filter bar, he has the worrying attack patterns, weaknesses, and vulnerabilities cataloged in the bucket.

Additionally, Garrett changes the system topology model slightly by removing the ZigBee attribute. By doing so, he notices that the radio modules are not part of the attack surface but they do still have associated attack vectors.

Garrett can immediately communicate all his findings to Emma since they both use the same tool by projecting the attacks in the bucket to the system topology, a familiar pane to Emma, who can further read and understand those attacks by clicking and seeing their description in a pop-up window.

Garrett and Emma conjointly present their findings to the rest of the stakeholders using intuitive and effective visualization techniques (Figure 5). Thus, they provide the stakeholders with defensible, traceable, and actionable evidence for alterations to the current system design. For instance, the stakeholders might decide to change the ZigBee radio module completely. Conversely based on the application and taking all information into consideration they might decide that the ZigBee range is too short for a practical attack, which then

they can capture in their mission-level requirements.

4 ALTERNATIVE APPROACHES

To our knowledge there is little to no work merging systems-theoretic analyses with traditional attack vector analysis for the visualization of CPS designs.

Connective structural and mission-oriented information is seen in MITRE CyGraph [30], which does graph-based analytics and does implement interactivity. A major deviation from this current work is that CyGraph is based on more traditional attack graphs [34], leverages different notions of mission impact, and it mainly targets traditional networked systems.

In traditional attack vector analysis there exist tools that mine security data and provide strong search functionality. One such tool is cve-search [5], which includes several more low-level security data repositories, for example, exploit-db [6]. However, cve-search has limited visualization capabilities and, more significantly, it does not provide interactivity—an important aspect of an analysis dashboard.

Recently, there has also been interest in the MITRE Adversarial Tactics, Techniques & Common Knowledge (ATT&CK) framework [36,37]. This framework allows security analysts to think in more general terms about consequences by providing different tables of choices that eliminate consequent choices. However, the current implementation is not well-suited for the design and analysis of CPS, because there are no external or operational goals that match the needs of those systems.

Another approach in the realm of model-based security analysis leverages topic modeling, which immediately relates system models to relevant CAPEC entries [8]. This approach can compliment the search engine that produces the data requirements for the dashboard.

In general, a similar rationale to this paper for visually constructing and presenting models is shown by Walton et al. [38]. In this work, we target CPS directly and expect the visualizations to be used from the early stages of the system’s lifecycle and updated often and

throughout including deployment and operation, while Walton et al. target deployment specifically.

The BioFabric [26] graph rendering algorithm could compliment the current view of the attack vector graph to deal with the inherent large size and complexity. This could potentially allow analysts to better understand how attack vectors relate to one another, which in turn provides quicker navigation of applicable attack vectors.

Finally, PERCIVAL [10] uses similar design choices (i.e., graph means and projections) to monitor and analyze computer networks. However, the domain (traditional information technology (IT) systems versus CPS) and the representation of exploitation (attack graphs [33] versus exploit chains) differ. This is important because the security needs of a traditional IT systems have significantly different expected consequences.

5 CONCLUDING REMARKS

In this paper we have proposed a merge between the advances in systems-theoretic security analysis and traditional attack vector analysis for the design and analysis of CPS. We capture this merge in an open-source security analyst dashboard and show how the complementary views can allow security analysis throughout the system's lifecycle—from the early-phase and beyond. Additionally, we show how such a dashboard makes security an attribute in system design equal to safety and how, by using a single tool, Systems Engineers and security analysts can communicate effectively. By doing this, we promote a proactive approach to security engineering, which is increasingly important in the realm of CPS, where the consequences of security violations lead to unsafe and uncontrolled behavior.

6 ACKNOWLEDGMENTS

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