HumIDIFy: A Tool for Hidden Functionality Detection in Firmware

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Overview

- COTS embedded device security is a disaster:
  - Poor coding practices.
  - Internet-facing “debug” interfaces.
  - Hard-coded credential checks.
  - Additional, hidden services.

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Overview (cont.)

- Lots of devices, lots of firmware (mostly Linux based).
- Multiple architectures (ARM, MIPS, PPC, etc.).
- Multiple firmware versions for each device.
- Manual analysis takes significant time and expertise.

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Existing Approaches

- A Large Scale Analysis of the Security of Embedded Firmwares (Costin, et al.).
- Automated Dynamic Firmware Analysis at Scale: A Case Study on Embedded Web Interfaces (Costin, et al.).
- Firmalice - Automatic Detection of Authentication Bypass Vulnerabilities in Binary Firmware (Shoshitaishvili, et al.).

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HumIDIFy

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Research Objective

- Address the problem of detecting additional, unexpected functionality in common services.
- A lightweight way to:
  - Identify classes of program functionality.
  - Identify anomalous functionality within those classes.

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Research Method

- A means to identify classes of program functionality:

  Use machine learning to identify classes of programs.

- A means to identify anomalous functionality:

  Use a DSL to define *expected* program functionality.

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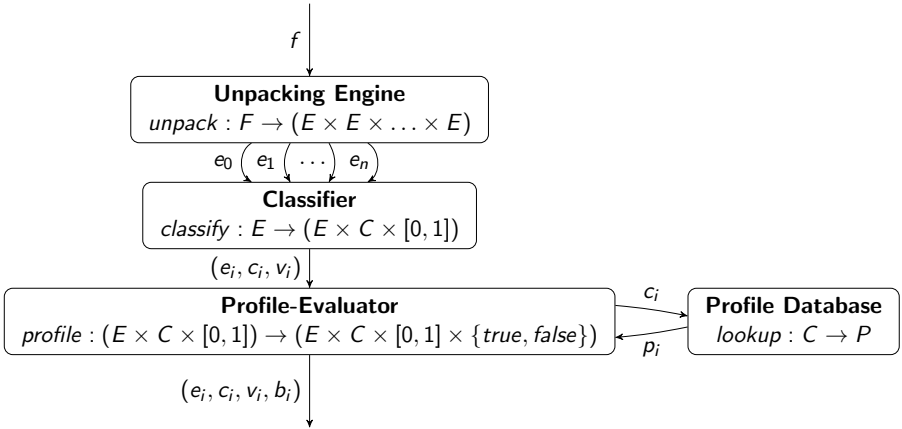
HumIDIFy



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Data-set Composition

- Collected set of firmware (15,438 images) from multiple vendors (30).
- Unpacked firmware reduced the data set to 7590 images (2,451,532 binaries).
- 3-way split of data set into training and validation sets and a further set for evaluation.

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Classifying Binary Functionality

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Attribute Selection

- Focus on features that are consistent across different architectures:
  - Strings.
  - Imported API names.
- Labels describe broad functionality categories (e.g. web server, etc.).
- Use `CfsSubsetEval` with `BestFirst` ranking.
- E.g. $\langle 1, 1, 0, \ldots, \texttt{web-server} \rangle$.

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Classifier Construction

- Semi-supervised learning:
  - What?
  - Why?

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Supervised Algorithm Evaluation

We first evaluated a number of supervised algorithms and selected the most optimal in terms of classification rate and time:

Classifier	Correct (%)	Time (s)
BayesNet	**88.4848**	**0.00**
NaiveBayes	79.3939	0.01
IBk	84.2424	0.00
KStar	84.2424	0.00
LWL	51.5152	0.00
JRip	66.6667	0.08
OneR	21.2121	0.00
PART	77.5758	0.04

Classifier	Correct (%)	Time (s)
ZeroR	10.9091	0.00
DecisionStump	20.6061	0.00
HoeffdingTree	79.3939	0.00
J48	76.9697	0.00
LMT	85.4545	0.90
RandomForest	88.4848	0.11
RandomTree	78.7879	0.00
REPTree	64.8485	0.03

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Bounded Self-Training

function BOUNDEDSELFTRAINING(labelledData, unlabelledData, v, bound)
  L ← labelledData, U ← unlabelledData, k ← 0
  loop
    train f from L using supervised learning
    (k', L', U') ← apply f to unlabelled instances in U where u ∈ U' if CONFIDENCE(f(u)) ≥ v
    if U = U' ∨ k' − k ≤ bound **then return** f
    end if
    k ← k', L ← L', U ← U'
  end loop
end function

Iteration	1	2	3	4	5	6	7	8
Correct (%)	88.4848	95.4819	97.0760	97.9021	98.5462	99.2366	99.3256	**99.3691**

Binary Functionality Description Language

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Binary Functionality Description Language

A simple domain specific language to express properties of programs:

rule uses_udp() = **exists** socket(*domain:int*, *type:int*, *protocol:int*) ⇒
if architecture("MIPS") **then** *type* == 2 **else** *type* == 1

rule may_read_files() = **exists** fopen(*filename:string*, *mode:string*) ⇒
(*mode* == "r" || *mode* == "r+" || *mode* == "w+" || *mode* == "a+")

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Binary Functionality Description Language

- BFDL is used to define the expected properties of a functionality class from the classifier.
- It is based upon a simple grammar that allows user-defined rules matching over both functional properties of code and meta data found within the binary being analysed.

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Binary Functionality Description Language

Features built-in rules to identify:

- Strings (and if they are referenced within code):
  `string_exists`, `string_ref`
- Function imports and exports (and if they are referenced within code):
  `import_exists`, `export_exists`, `function_ref`
- Function usage - if and how a function is used (and analyse the properties of the arguments passed to it):
  `exists f(x:int, ...)` $\Rightarrow$ `(x = ...)`, `forall f(...)` $\Rightarrow$ `...`

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Binary Functionality Description Language

Examples

import "prelude.bfdl"

rule web_server() = uses_tcp() && !uses_udp() && may_read_write_files()
&& !outgoing_socket()

rule puts_x(*x:string*) = **exists** puts(*v:string*) ⇒ *v* == *x*

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Expected Functionality Classifier + Functionality Checker $\approx$ Anomalous Functionality Detector

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Evaluation & Results

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Evaluation of Classifier

For a total of 24 different functionality classes:

- Classification rate of 99.3692% on training data
- Classification rate of 96.4523% on separate test data (manually labelled - 451 binaries)

For the most common services our classifier is highly effective in assigning the correct functional class to a given binary.

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Evaluation of Classifier

Misclassified instances were generally due to overlapping functionality:

- `busybox` implements a large amount of diverse functionality.
- API usage overlapping in network-based services caused some mislabelling.
- Most commonly mislabelled functionality class "nvram-get-set" is a label describing binaries that perform reads/writes from the NVRAM, usually used to preserve user configuration data. This was largely due to how device vendors implement such functionality: some use calls to external programs (e.g. `nvram-get`, `nvram-set`), others implement the functionality directly.

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Evaluation of HumIDIFy

- Evaluated on "artificial instances": we added an extremely simple UDP-based backdoor in `mini_httpd` and `utelnetd`.
- We tested unmodified instances of each using HumIDIFy to observe the classification (both classified correctly).
- Performed the same classification attempt upon the modified binaries: produce the same classification and feature vectors.
- Both unmodified binaries are passed as fine, both modified binaries are detected as anomalous – both fail to meet their expected functionality profile.

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Evaluation of HumIDIFy on Real World Firmware

From 392 unique binaries from 100 firmware images, 9 were flagged as anomalous by HumIDIFy:

- A web server containing a previously documented "management interface" backdoor providing shell execution upon the device.
- A web server with a built-in DNS resolver.
- Custom service implementing an Internet telephony proxy detected as a TCP daemon, but supported UDP as a means of data exchange.
- A custom service implementing HTTP proxy functionality, part of Trent Micro kernel engine additionally using UDP to communicate.

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Run-time Performance

Average run-time performance statistics:

- Attribute extraction: 1.31s.
- Classification of single binary: 0.291s (not including time taken to invoke the Java virtual machine).
- Performance of DSL evaluator is dependent upon the complexity of the binary under analysis (number of functions and complexity of the functions): 1.53s on average.
- Time to process an "average" firmware image: 970.61s.
- Performance analysis does not take into account the human factor in final manual analysis.

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Limitations & Security Analysis

Can we evade HumIDIFy?

- Current analysis relies on ability to extract imported symbols.
- We look for a specific class of unexpected functionality.

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Limitations & Security Analysis (cont.)

- What about binaries that deliberately attempt to masquerade as something else?

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Conclusion

- We construct a classifier to identify functionality in common services in Linux-based firmware.
- We develop a domain specific language to define the expected functionality of such common services.
- By combining the two components we are able to identify common services that exhibit anomalous functionality.

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Questions?

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