

Enabling Deep Visibility into VxWorks-Based Embedded Controllers in Cyber-Physical Systems for Anomaly Detection

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Abstract—We propose the DIVER (Defensive Implant for Visibility into Embedded Run-times) framework for real-time deep visibility into embedded control devices in cyber-physical systems (CPSs). DIVER enables run-time detection of anomalies and is targeted at devices running the real-time operating system (RTOS), VxWorks, which precludes traditional methods of implementing dynamic monitors using OS (e.g., Linux, Windows) functions. DIVER has two components. The “measurer” implant is embedded into the VxWorks kernel to collect run-time measurements and provide interactive/streaming interfaces over a TCP/IP port. The remote “listener” acquires and analyzes the measurements and provides an interactive user interface. DIVER focuses on small embedded devices with stringent resource constraints (e.g., insufficient storage to locally store measurements). We demonstrate efficacy of DIVER on the Motorola ACE Remote Terminal Unit used in CPS including power systems.

Index Terms—Anomaly detection, PLC, real-time operating system, VxWorks, Embedded systems, Defensive implant, Remote monitoring.

I. INTRODUCTION

With growing complexity, connectivity, and remote programmability and configurability of embedded control devices in cyber-physical systems, robust cyber-security and anomaly detection techniques are becoming increasingly vital [1]–[3]. The need for such techniques is becoming more crucial with sophisticated adversaries able to transit from the information technology (IT) network to the operational technology (OT) network and exploit vulnerabilities of embedded devices to insert malicious code, alter device configurations, or modify their behavior. Through such adversarial manipulations, adversaries can severely disrupt the operation of the cyber-physical system (CPS) and potentially cause catastrophic consequences to the stability, safety, or performance of the CPS. Hence, development of real-time monitoring and anomaly detection techniques has been intensely studied and several approaches have been proposed based on techniques such as network traffic monitoring, host-based intrusion detection, side channel analysis, etc.

While host-based methods using operating system (OS) level observations such as system call traces and registry

modifications can be effective for devices running general-purpose operating systems such as Linux or Windows, they are not directly applicable to embedded devices that run real-time operating systems (RTOS) such as VxWorks, QNX, or FreeRTOS. Such embedded devices are prevalent in CPS such as power grid due to their real-time performance, robustness, simplicity, and reliability. The development of corresponding host-based monitoring methods for such devices faces multiple challenges due to, for example, the monolithic structure of such RTOS (e.g., no separate processes), constraints of their software ecosystem (e.g., do not expose a command-line shell or only provide a shell under a special debug mode that requires a device reset and is very different from normal mode, difficulties in deploying custom code), and device-level limitations (e.g., limited disk space to store measurements). While the human-machine interfaces (HMIs) of these devices provide some visibility into the device operation, malware on the devices can easily spoof these observations and cloak the presence of the malware. Hence, a deep under-the-hood visibility into the device run-time operation is crucial to establish integrity of the devices.

To address this vital need, we develop the DIVER (Defensive Implant for Visibility into Embedded Run-times) framework (Figure 1) in this study for achieving real-time deep visibility into embedded control devices (e.g., programmable logic controllers and remote terminal units). DIVER is intended to enable real-time introspection and anomaly detection by embedding a defensive implant (“measurer”) directly into the RTOS to enable under-the-hood monitoring of run-time measurements (of various types including RTOS task-level activity measurements, device status, firmware module information, timer interrupt configurations, memory and filesystem contents, etc.). This implant communicates with a remote monitoring agent (“listener”) via a TCP/IP channel to exfiltrate real-time measurements from within the RTOS. The listener analyzes these measurements to build a real-time situational awareness of the device execution state and detect anomalies relative to prior observations or baselines. The listener also provides an interface for interactive commands to be relayed to the VxWorks-embedded implant – this interface can be used both by human operators or automated scripts. The DIVER framework focuses on small embedded resource-constrained devices such as programmable logic controllers (PLCs) and remote terminal units (RTUs) in CPS. For the proof-of-concept, we demonstrate the framework on the Motorola ACE RTU [4] that runs the VxWorks RTOS.

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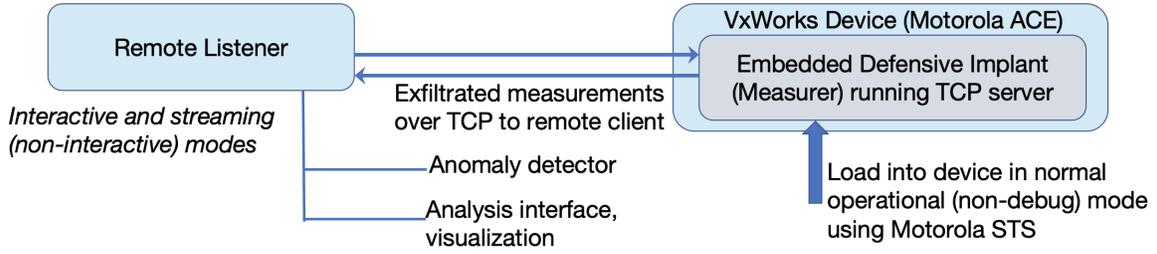


Fig. 1: Structure of the DIVER framework comprising an embedded defensive implant (“measurer”) that starts a TCP server to allow connection from a remote client (“listener”) to provide an interactive user interface and to exfiltrate measurements.

II. BACKGROUND AND RELATED WORK

While RTOS such as VxWorks and QNX are popularly used in embedded control devices due to their deterministic real-time properties, performance, robustness, and reliability, they are not immune to vulnerabilities that can be exploited by adversaries. For example, a set of zero-day vulnerabilities (URGENT/11) discovered in the VxWorks RTOS in 2019 [3] was found to potentially affect billions of devices across various industries. Vulnerabilities specific to particular devices such as the Motorola ACE RTU have also been noted [5]. Several classes of vulnerabilities have been identified across a broad range of embedded devices across several major vendors [6] and have been found to potentially allow attackers to gain unauthorized access to devices to manipulate their configurations, modify their code, and alter their behavior. The detection of such vulnerabilities underscores the need for robust real-time monitoring and anomaly detection. Devices running general-purpose OS such as Linux and Windows can leverage OS-level functionalities [7] to facilitate monitoring and anomaly detection using various “side channel” observations (e.g., system call traces, stack traces, registry keys, enumerations of processes and dynamically loaded modules, Hardware Performance Counters – HPCs, etc.). On the other hand, devices running RTOS such as VxWorks pose unique challenges to development of corresponding monitoring methods. While network-based monitoring methods (such as protocol payload anomaly detection [8]) can be device-agnostic, host-based methods need to address the challenges of integrating into an RTOS, deploying such custom code, extracting run-time measurements that provide a comprehensive view of the device operation, and exfiltrating these measurements to a remote monitoring agent. These challenges have also been discussed in [9], where a host intrusion detection system was developed to collect system logs and RAM usage measurements from a Bosch Rexroth AG IndraControl XM device with an Intel Atom processor running VxWorks. Since integrating monitoring methods into the device RTOS is challenging, off-device approaches have been studied based on methods such as evaluating input-output behaviors using offline copies of PLC programs [10], symbolic execution and model checking to analyze PLC control logic [11], and measurements of program execution times using vendor-provided tools to detect timing anomalies during the scan cycle of the PLC [12].

In comparison with the prior work discussed above, the DIVER framework provides several unique contributions: (1)

it enables collection of dynamic task-level measurements providing deep visibility into the run-time behavior rather than relying upon built-in logging behavior which could be circumvented by adversaries – the dynamic time series measurements are analogous to process-level measurements that could be obtained on devices running general-purpose OS and can enable detection of subtle dynamic activity changes on the device; (2) it enables real-time exfiltration of measurements through a streaming interface over a TCP/IP channel to a remote monitoring agent, removing requirement for any storage on the device itself; (3) it enables an interactive interface to the device implant for real-time command and control, which can be used to dynamically query the device, perform actions, and enable a moving target defense against adversaries; (4) it is designed to be lightweight and scalable to support highly resource-constrained embedded devices.

III. DIVER FRAMEWORK

A. Threat Model

The DIVER framework is designed to address the threat model where an adversary either (a) uses some existing vulnerability in the device to gain unauthorized access and deploy new code or modify existing code to manipulate the operation of the device; or (b) modifies network traffic or other inputs to the device to cause changes to the device operation. The proposed DIVER approach seeks to address the general change detection problem by flagging behavioral changes that could be due to attacks, malfunctions, process-level changes, etc., and serving as an alarm mechanism to alert operators on unexpected behavioral modifications of a device. To enable such on-demand integrity verification, the defender is assumed to be able to access the device (remotely or physically) and deploy a defensive implant into the device RTOS using the proposed DIVER framework. Thereafter, DIVER opens a remotely accessible port to stream measurements from the device to enable remote monitoring and anomaly detection.

B. Overall Framework

The DIVER framework addresses an embedded device running an RTOS (specifically VxWorks) and comprises of two components as illustrated in Figure 1:

- An on-device defensive “measurer” implant is deployed to the device (typically using device-specific vendor-provided tools such as the Motorola STS software suite for Motorola ACE device).

- An off-device “listener” (i.e., remote monitoring agent) that communicates via a network connection with the on-device component to retrieve measurements from the device as well as to enable on-demand execution of commands on the device.

While the on-device component depends on device-specific details such as the appropriate compiler toolchains and deployment mechanisms, its core architecture is scalable between devices and comprises of the following primary components: a TCP server, an embedded scripting engine for run-time configurability from the listener agent, a set of function callbacks exposed via the scripting engine for use by the remote listener to invoke device operations/measurements on demand, back-end functions that acquire measurements of the device activity (these back-end functions are the ones that are primarily dependent on device-specific details). The off-device remote listener is agnostic of the specific devices to a large extent and is a general-purpose change detection and user interface module. The on-device/off-device hybrid architecture of DIVER is motivated by multiple considerations. Firstly, embedded VxWorks devices (such as Motorola ACE) do not provide any remote access to retrieve measurements (e.g., no secure shell access) except for device-specific HMI which communicate using proprietary protocols, provide only limited visibility of device activity, and themselves might be the target of attacks by adversaries. Hence, DIVER’s defensive implant instead makes available a separate parallel communication channel that is independent of vendor-provided functionalities. Secondly, the embedded devices of specific focus for DIVER are small and have limited memory, storage, and processing capabilities. Hence, instead of attempting to perform anomaly detection algorithmic computations on the device, DIVER leverages off-device computational capabilities accessible to the remote listener to enable flexible algorithmic designs for data analysis and anomaly detection while keeping the on-device component light-weight to fit within the stringent limitations of the embedded device. Thirdly, by decoupling the on-device and off-device components, DIVER enables device-independent off-device data analysis and interactive user interface which can be used not only to visualize retrieved data but also to run on-demand operations on the device via the embedded scripting engine.

The on-device defensive implant implements a library of measurement functions on the device that are accessible to the remote listener to execute on-demand and retrieve data or configure for periodic execution to receive data in streaming mode. The scripting-based automation framework embedded into the implant enables flexible configuration of sets of measurements and their sampling periodicities and granularities. Thus, the implant enables remote visibility into a device that in off-the-shelf mode, does not provide any mechanism for such visibility. Using the retrieved measurements from the device, the remote listener can register a baseline (during training on a known-good device) or analyze for anomalies (during integrity verification of a device in the field) and more generally, detect changes in device activity over time (same device at different points in time) or over space (across multiple

devices in the CPS configured similarly and expected to have similar behaviors). The on-device and off-device components are discussed in more detail in the next subsection.

C. Implant and Listener Architectures

The architectures of the implant and listener components are illustrated in Figure 2. Upon deployment, the defensive implant starts a TCP server on the device allowing connections from remote clients. When a remote client connects, the implant initiates a query-response loop to process commands sent from the remote client. The query-response module connects to a scripting engine to perform the command-specific actions on the device using a library of back-end functions for acquiring device-level measurements or performing device operations such as setting configuration parameters or performing I/O operations. The implant is designed to be lightweight and modular, allowing for easy addition of new measurement functions as needed. The query-response loop continues until the client disconnects or times out, at which point the implant closes the connection and cleans up any remaining state from the client. The implant supports parallel connections from multiple clients to allow, for example, multiple operators to connect simultaneously through command-line or browser front-end interfaces. After the initial connection from a client, subsequent communications can use a light-weight encryption of the payload with an embedded session identifier to prevent adversaries from eavesdropping, sending unauthorized commands, or mounting replay attacks.

Two variants of the scripting engine were implemented. The first is a simple text-based format structured as a command name with parameters to specify operations to be performed on the device and corresponding configuration parameters (e.g., read task-level information with a configurable granularity setting and specify a sampling rate for streaming mode retrieval). The second is a full-featured scripting engine based on the Lua programming language and allows for execution of more complex scripts on the device (e.g., performing a measurement or an I/O operation based on a specific condition such as when resource usage exceeds a specified level, setting up custom timer-based callbacks for operations to be performed after a specified time).

The back-end function library (details of implementation using VxWorks/device APIs discussed as part of the next section) provides several device-level measurement functionalities such as:

- List of running tasks, task names and task IDs.
- Task-level measurements of task status, program counter, stack pointer, link register, task priority, entry point, etc.; task-level measurements of activity levels based on percentages of time in READY state, variability in program counter for the task, etc.
- System diagnostics (versions of VxWorks kernel and libraries, input/output configurations, uptime, system database, etc.).
- Loaded modules and C applications on the device along with details such as file location on the device, addresses of the jump table and control function, hashes of initial memory segments of modules/applications, etc.

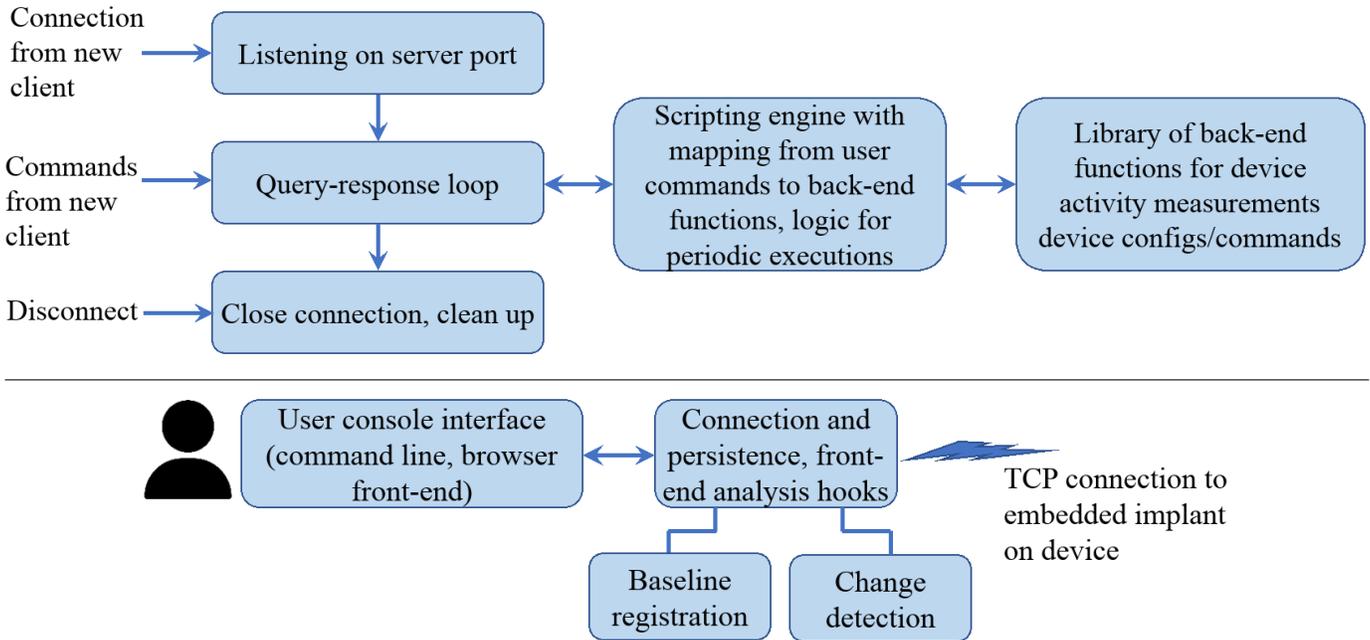


Fig. 2: Architectures of the on-device defensive (top) and the off-device remote listener (bottom).

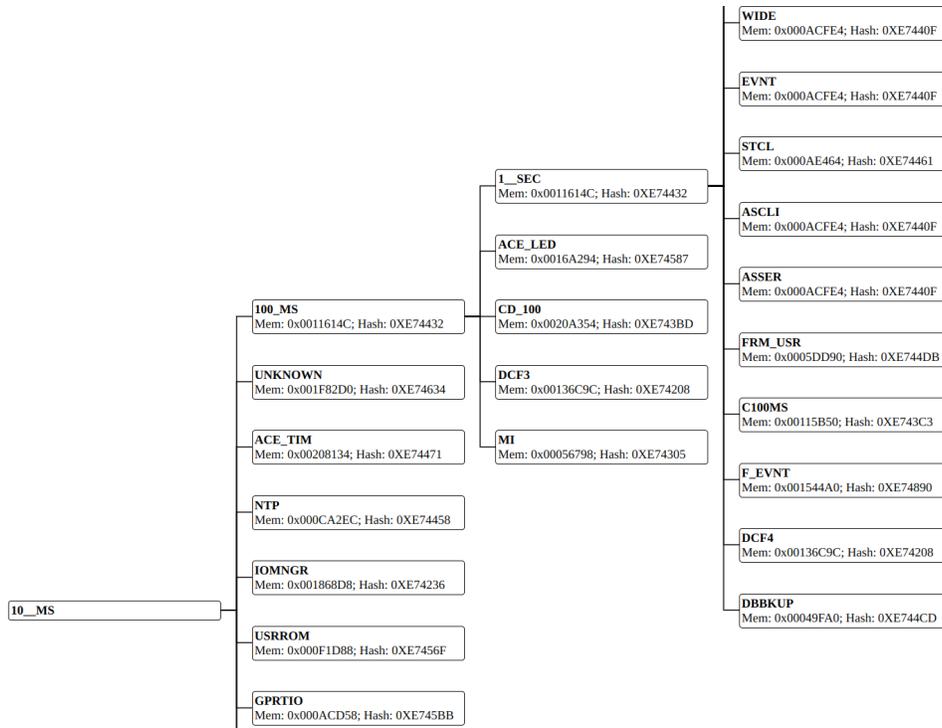


Fig. 3: Sample snippet of a timer tree reconstructed from measurements exfiltrated from a Motorola ACE by the embedded defensive implant.

- Readings from the device diagnostics and system log mechanisms. For this purpose, the implant uses a flexible parser implemented to read the binary format used internally by the device diagnostics and system log functionalities on the Motorola ACE.
- Binary contents of ranges of memory locations.
- Full timer tree with callback pointer locations and code hashes – the timer tree is a hierarchical structure defining

the relations between the primary timer and the lower-frequency timers iteratively derived from it and the callbacks registered at each level of the tree.

In addition, the implant allows actions such as

- Reading and writing analog and digital inputs and outputs on the device.
- Reading and writing to the diagnostics and system log buffers.

- Reading and writing to the device’s flash memory.
- Registering callback functions implemented in the scripting language to a specified timer in the timer tree to be executed periodically.
- Reading and writing the device’s time and date.
- Reset the device.

The remote listener is implemented in Python and connects to the embedded implant via a TCP/IP channel and interacts with the query-response loop component of the implant. The listener provides an interactive command-line user interface for operators to issue commands and view responses from the implant. The command-line interface is structured using the format for the simple text-based scripting engine described above. When the full-featured scripting engine is enabled, the command-line interface also provides functions for the operator to send over script snippets to be executed on the device. The listener also provides a browser-based front-end interface, which refreshes automatically when receiving data in streaming mode and also provides visualizations of retrieved data such as the timer tree as well as color-coded visualizations of anomaly detection analysis results (Figures 3 and 4). The browser-based interface is implemented using HTML and JavaScript with the content dynamically created by the Python-based listener.

The listener includes a data analysis module that processes the retrieved measurements to build a model of the device activity. This generated model can be specified to be used as a baseline model (e.g., during training on a known-good device) or as a model to be evaluated (e.g., during integrity verification of a device in the field). The various types of measurements available to be exfiltrated via the implant as discussed above enable comprehensive change detection at multiple levels. For example, changes in the device configuration such as network settings, timer configurations, timeout parameters, etc., are immediately flagged. Addition/deletion of modules or tasks are also directly observed. Furthermore, since hashes of the memory segments of modules, etc., are retrieved, changes to existing modules are also flagged. Any new timer callbacks are also detected. Following these low-level change detections, the anomaly detector analyzes the more granular measurements such as task-level states, activity levels, priorities, etc., to detect statistical changes in the device behavior. In streaming mode, the basic semantic structure for activity analysis as discussed above is a time series of snapshots of running tasks on the device along with task-level observations such as the task states (READY, SLEEPING, etc.), task priorities, registers such as program counter and stack pointer, etc. By comparing statistical properties of an observed time series of snapshots against statistical properties of a baseline set of measurements, anomalies based on detected statistical differences are flagged. Variations in observed statistical properties of temporal distributions of task states, measured ranges of registers such as program counter and stack pointer (per-task and across all tasks) compared to baseline observations show fine-grained modifications in the overall device activity that could result from adversarial manipulations or other changes in the device operation. For example, a task that is much more or much

less in READY state compared to the baseline or a task that is in pending state (PEND) when it was typically in READY state in the baseline indicate anomalous changes in the device operation. The listener generates alerts or notifications automatically in the browser-based front-end when anomalies are detected, allowing operators to take appropriate remediation actions.

IV. PROTOTYPE IMPLEMENTATION AND EXPERIMENTAL STUDIES

For the proof-of-concept experimental studies in this paper, we deployed DIVER on the Motorola ACE3600 RTU [4], which is a real-time process automation device designed for SCADA (Supervisory Control And Data Acquisition) systems in CPS such as power grid. The ACE3600 has a 32-bit 200MHz PowerPC processor running the VxWorks RTOS. The device features a modular design accommodating several types of input/output (I/O) modules (both digital and analog inputs and outputs). It supports several OT (Operational Technology) communication protocols such as the industry-standard Modbus, DNP3, M-OPC, and IEC60870-5-101, as well as Motorola’s own MDLC protocol. Motorola’s ACE3600 System Tools Suite (STS) is a vendor-provided Windows-based software that provides tools to administer ACE3600 devices, set up their configurations, and download files or code modules to the devices. Additionally, Motorola’s C Toolkit for ACE3600 RTUs with the MOSCAD (MOTOROLA SCADA) APIs provides a toolchain (cross compiler, linker, etc.) for compiling C code into a dynamically loadable module packaged into a compressed file (.plz), which can then be downloaded using STS into the device. Upon downloading to the device, the module is dynamically loaded into the device’s memory and starts executing at a predefined module entry point (`user_control_function`). From this entry point, new tasks can be started to be executed in the background using VxWorks APIs or MOSCAD APIs which are a thin layer on top of the VxWorks APIs. Additionally, functions to be periodically executed can be registered by connecting them to one of the entries in the device’s timer tree (e.g., 10ms, 100ms, 1s, etc.) by providing a callback pointer for the function. To access VxWorks APIs via symbol resolution during dynamic loading, the required VxWorks function declarations (e.g., `taskIdListGet` from VxWorks’ `taskInfo` library to obtain a list of active task IDs) are included in the C code module along with the required C structure definitions (e.g., `TASK_DESC` from VxWorks’ `taskShow` library to obtain detailed task-level information) based on separately publicly available VxWorks documentation. These APIs facilitate the various implant functionalities described in the previous section such as obtaining high-granularity measurements of device activity and accessing networking functionalities such as starting a TCP/IP server for remote communication.

The implemented DIVER prototype was deployed on the Motorola ACE RTU. Samples of measurements retrieved using the DIVER prototype are shown in Figures 3-5. The visualizations of the sample timer tree and the summary snippets in Figures 3 and 4, respectively, are from the browser-based

Tasks on device:

```

■ ■ tSMITSLY : Entry point = 0x3CC944; Memory hash = 0XE74764; Task priority = 254 ; Current stack usage: 176 bytes; Max stack usage: 544 bytes
■ ■ tNetTask : Entry point = 0x419B44; Memory hash = 0XE7495E; Task priority = 50 ; Current stack usage: 224 bytes; Max stack usage: 2064 bytes
■ ■ tDhpcStateTask : Entry point = 0x40AC98; Memory hash = 0XE7484E; Task priority = 56 ; Current stack usage: 240 bytes; Max stack usage: 304 bytes
■ ■ tDhpcReadTask : Entry point = 0x4059CC; Memory hash = 0XE74499; Task priority = 56 ; Current stack usage: 608 bytes; Max stack usage: 784 bytes
■ ■ tPortmapd : Entry point = 0x4976FC; Memory hash = 0XE745BA; Task priority = 54 ; Current stack usage: 576 bytes; Max stack usage: 752 bytes
■ ■ tWdbTask : Entry point = 0x49DC38; Memory hash = 0XE746AF; Task priority = 3 ; Current stack usage: 64 bytes; Max stack usage: 64 bytes
■ ■ tShell : Entry point = 0x46AA5C; Memory hash = 0XE743F9; Task priority = 1 ; Current stack usage: 1040 bytes; Max stack usage: 1280 bytes
■ ■ MTE_VLD : Entry point = 0x1ABB80; Memory hash = 0XE74916; Task priority = 255 ; Current stack usage: 224 bytes; Max stack usage: 1504 bytes

```

```

[CAPPL] CAPPL_NUM_100MS_TIMERS=10      ( 'tasks_states_frequent_to_infrequent',
[CAPPL] CAPPL_NUM_10MS_TIMERS=0        [( 'TL_PLCB', 'READY'), ('TL_PLCC', 'READY')]),
[FIREWALL] AVOID_GRATUITOUS_ARP=1      ( 'tasks_states_infrequent_to_frequent',
[I2C] I2C_BAUD=100000                  [ ('LOGFLAS', 'PEND+T'),
[I2C] I2C_IS_BIT_ORDER NORMAL=1        ('TCHNLTS', 'DELAY'),

```

```

udp_tep.pl : Location = z:/TEPs; Jump table address = 0x06241F10; Control function address = 0x06241CD0; Memory hash = 15155467

```

Fig. 4: Sample snippets of the summaries and detected anomaly listings generated by the remote listener using measurements exfiltrated by the embedded defensive implant. Top row: snippet of task activity summaries (two color-coded icons on the left of the task names indicate the activity levels of the tasks in terms of percentage of time the task is in READY state and the amount of variations seen in the program counter for the task (red indicates more active). Middle row: snippets of device configuration (left) and task state statistics changes (right) compared to a baseline. Bottom row: snippet of flagging of an unknown C application loaded on the device.

front-end of the listener. The timer tree in Figure 3 shows the hierarchical structure of the timers on the device, with the primary timer at the left and lower-frequency timers derived from it on the right. The callbacks registered at each level of the tree are also shown, along with their corresponding memory locations and code hashes. The summary snippets in Figure 4 show various types of measurements retrieved from the device, including task-level information and device config and example anomaly alerts. The sample anomalies shown in Figure 4 indicate changes in task state statistics compared to a baseline and presence of an unexpected C application on the device along with its file location, memory addresses, and hash of the initial segment of the memory contents of the loaded application. The unexpected C application flagged in Figure 4 is a malware that sends a stream of UDP packets via a background task started by the malware. Sample time series of task states are shown in Figure 5, where each colored dotted line represents a different task and the Y-axis shows the different states that were observed for the tasks: READY (task is ready to execute and is only waiting to be scheduled on the CPU), PEND (task is blocked since some required resource is not available), PEND+T (similar to PEND except that it also has a timeout), DELAY (task is sleeping for a time interval), SUSPEND (task is not available for execution), etc. It is seen that there are clearly discernible temporal patterns in the state transitions of the tasks indicating the task behaviors. The right-side plot in Figure 5 shows the numbers of tasks in each of these states at each sampling time instant. In this sample data, the sampling rate was set to 1 Hz in streaming mode. As discussed in the previous section, the multiple types of measurements retrieved by the implant enable several types of change detection. Apart from insertion of unexpected C application modules as illustrated in Figure 4, other types of modifications such as changes in the timer tree configuration and replacement of existing modules were also tested and verified to be detected by DIVER. Specifically, insertion of new callbacks into the timer tree to be periodically executed were flagged. Also, modifications of existing modules were detected from mismatches in the corresponding memory hashes. Other

modifications such as disabling existing tasks, changing task priorities, and uploading new files were also studied.

V. DISCUSSION AND CONCLUSIONS

This study develops the DIVER framework that enables deep real-time visibility into the run-time operation of embedded control devices in CPS. The DIVER framework is architected as a combination of two interconnected components: a defensive implant deployed into the RTOS of the embedded device that opens a custom TCP/IP server for the purpose of exfiltrating measurements and enabling an interactive command interface; a remote listener that acquires measurements from the implant via a TCP/IP connection and evaluates the integrity of the measurements against prior/baseline observations for anomaly detection and also provides an interactive console to relay commands to the defensive implant. The DIVER framework is designed to support lightweight embedded devices with stringent resource constraints. DIVER specifically focuses on VxWorks devices due to their prevalence in various CPS such as power grid and industrial control systems and due to the unique challenges posed by such devices that have stringent resource constraints and on-device limitations that preclude traditional monitoring methods.

We demonstrated the efficacy of the proposed DIVER framework on the Motorola ACE RTU. By deep integration into the bare-metal RTOS layer of the embedded device, DIVER enables detection of stealthy adversarial modifications that might not have evident manifestations in the higher-level application layer or in the device's input-output behavior and therefore not detectable by traditional monitoring methods. Furthermore, while DIVER focuses on detection of malware/anomalies on the device, DIVER can also indirectly enable detection of attacks on the HMI by being able to flag mismatches between the on-device measurements and the HMI's view of the device operations. Also, while DIVER primarily addresses detection of changes from a baseline, DIVER's real-time visibility into the device operation can also be used to extract salient properties of device activity even in

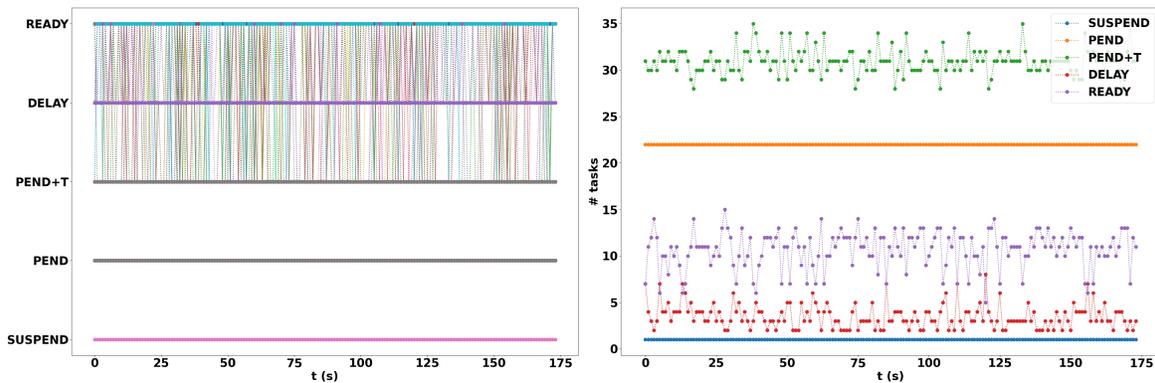


Fig. 5: Left: Sample time series of task state measurements; each colored dotted line represents a different task. Right: Numbers of tasks in each state (READY, PEND, etc.) at each sampling time instant. The time series and the state counts are obtained from measurements exfiltrated from a Motorola ACE by the embedded defensive implant.

the absence of an available baseline, e.g., to identify tasks with most activity or using most resources (i.e., analogous to a tool such as `htop` on Linux). Through integration of a scripting engine into the defensive implant and a remotely available interactive console in the listener, DIVER enables dynamic configurability and on-demand execution of commands on the device.

The DIVER framework is designed to be agnostic to the specific device under observation and can be adapted to other embedded devices and can also be extended to support additional types of measurements and anomaly detection techniques. Also, DIVER’s modular on-device/off-device structure and the real-time visibility of device activity and exfiltration of time series measurements enabled by DIVER can benefit third-party monitoring and event detection systems to assist in remote integrity verification. Future work will focus on enhancing the DIVER framework to support additional types of measurements and anomaly detection techniques, and on evaluating the framework on a broader range of embedded devices in CPS.

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