FIRED: Frequent Inertial Resets with Diversification for Emerging Commodity Cyber-Physical Systems

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Abstract
A Cyber-Physical System (CPS) is defined by its unique characteristics involving both the cyber and physical domains. Their hybrid nature introduces new attack vectors, but also provides an opportunity to design new security defenses. In this paper, we present a new domain-specific security mechanism, FIRED, that leverages physical properties such as inertia of the CPS to improve security.

FIRED is simple to describe and implement. It goes through two operations: Reset and Diversify, as frequently as possible - typically in the order of seconds or milliseconds. The combined effect of these operations is that attackers are unable to gain persistent control of the system. The CPS stays safe and stable even under frequent resets because of the inertia present. Further, resets simplify certain diversification mechanisms and makes them feasible to implement in CPSs with limited computing resources.

We evaluate our idea on two real-world systems: an engine management unit of a car and a flight controller of a quadcopter. Roughly speaking, these two systems provide typical and extreme operational requirements for evaluating FIRED in terms of stability, algorithmic complexity, and safety requirements. We show that FIRED provides robust security guarantees against hijacking attacks and persistent CPS threats. We find that our defense is suitable for emerging CPS such as commodity unmanned vehicles that are currently unregulated and cost sensitive.

1 Introduction
A Cyber-Physical System (CPS) represents the synthesis of computational and physical processes encompassing a wide range of applications including transportation, medical, robots, and power grids. CPSs usually consist of a controller, sensors, actuators and a network. Known attacks, academic and real-world, on CPSs are diverse and span both the cyber and physical domains. Cyber attacks like the Jeep Hack by Miller et al. [24] and Tesla remote hack by the Keen group [3] and physical attacks such as those on car sensors by Yan et al. [11] are just a few that have appeared in the media recently. The dangers were first highlighted by the pioneering work of Koscher et al. [22] and Checkoway et al. [10].

Current state of the art defenses for CPSs can be understood as defenses for the physical portion of the CPS, viz., the sensors, and cyber portion of the CPS, viz., the control and communication software. The physical defenses leverage physical properties to detect and mitigate sensor spoofing, sensor jamming, and other similar types of attacks. Current cyber defenses, typically designed for more traditional systems, are usually incompatible for a CPS due to timing or computing constraints but have been adapted by modifying some of the operational parameters.

In contrast to current cyber defenses for CPSs, which are adaptations of cyber defenses, in this paper, we propose a new software security defense for CPS that leverages unique properties of CPSs. A key innovation in our approach is that we take advantage of inertia, i.e., the ability of the CPS to stay in motion or at rest, and its ability to tolerate transient imperfections in the physical world, to survive attacks. Basically we reset the controller software as frequently as possible without impacting safety. The security benefit of the frequent reset defense is that it limits the time for which the system is vulnerable to attacks. Additionally, diversification is used to force the adversary to develop a new attack strategy after every reset; that is, attacks after each reset should be independent of each other, lowering the likelihood of an attack’s success.

Our system, FIRED, is best understood with an example. Consider a drone: even if power is cut off to the engine, the drone will continue to glide due to inertia; similarly, even if a few sensor inputs are incorrect, the drone
will continue to operate safely because intermittent sensor errors happen in normal operation and controllers are designed to handle this case. In FIRED, we take advantage of these features. We intentionally reset the system periodically to clear state that may have been corrupted by an attacker. During resets, we rely on system inertia to continue operating, and we diversify to prevent the same attacks from breaking the system.

It is easy to see why FIRED is uniquely suited to CPSs as a defensive technique. If traditional digital, non-physical systems are reset frequently, because they lack inertia, they cannot independently survive resets. To wit, consider resetting a server every few network packets. In order to recover from missed packets, an external entity needs to retransmit them. In contrast, in a CPS, the feedback loops present help them independently rebuild the state that might have been lost due to the reset. Additionally, the physical components of the system, due to inertia, continue operating even when there is no computation by the controller. Finally, the network packets can arrive in the order of nanoseconds in a traditional digital, non-physical system while the reset times are in the order of seconds. For CPS data often arrives on human scales (milliseconds) and reboot times are also much shorter.

Realizing FIRED for CPSs is not without challenges. While all CPSs have inertia, the amount of inertia they have is variable. Resetting too frequently may cause the safety requirements of the system to be violated if the inertia cannot cover the operational and safety requirements during controller downtime during reset. Further, computational resources are constrained on most CPSs due to cost and power requirements. In this paper we show a systematic method to determine the frequency of reset and an implementation of FIRED that allows CPS to be secured in a pragmatic way.

We evaluate FIRED on two popular CPSs with different inertia and safety requirements. Using an open source engine controller—rusEFI—and measurements from a real combustion engine, we discuss and measure the performance and safety impacts. Additionally, we evaluate FIRED on a Flight Controller (FC) for a quadcopter which exhibits more limited inertia. We find that both of these systems tolerate multiple frequent resets. The engine can tolerate resets at intervals of 125ms while the quadcopter at an interval as frequent as a second. We additionally define appropriate safety requirements for each and show that FIRED does not violate them. Thus, FIRED provides a novel way for enhancing the security of CPSs without impacting safety, with low resource requirements, and a simple implementation using unique properties of CPSs.

The rest of the paper is organized as follows: In the next section we describe a system model for a CPS system that we use, in the following section we describe the attack model. We then describe our FIRED technique in Section 4, and evaluate FIRED on representative case studies—an Engine Control Unit (ECU) and a Flight Controller (FC)—discussed in Section 7. We conclude in Section 10 with applicability and limitations.

2 System Model

Overall Architecture: Current CPSs have four main subsystems: a subsystem that interfaces with the physical world that includes the sensors and the actuators, a subsystem that takes inputs from the sensors and generates commands for the actuators—the control subsystem,—a subsystem that takes in external commands, and finally a subsystem the provides non-critical functions such as entertainment subsystem. In most CPSs today these subsystems are not isolated from each other creating a quagmire of security problems. However, recognizing these dangers, emerging CPS designs include primitives for isolation (such as separating out the networks in a car), sensor authentication and encryption to name a few.

We set our work in this emerging model and we consider the safety and security of only the software that provides control over the physical system (i.e. the safety critical components). The enclosed portion of Figure 1 illustrates our model. The rationale for this choice is to focus our attention on aspects that are unique to CPS. A wide variety of systems fall into this model, such as unmanned transport vehicles or industrial control systems.

Resource Model: CPS resources can vary wildly. However, a large subset of these systems rely on microcontrollers. They tend to execute from ROM or Flash chips with limited memory (typically hundreds of KBs or a few MBs), have no memory management unit (MMU), only a memory protection unit (MPU); and the performance offered by these microcontroller-based systems
CPS Properties: With these system and resource models in mind, we can begin to discuss some of the important properties of cyber-physical systems that allow for interesting security techniques to be explored. These properties stem from the design, algorithms, and physics of CPSs. The main properties of CPSs are:

* They move. CPSs operate in the physical domain and as a result involve some form of lateral or rotational motion. This motion leads these systems to have inertia—the resistance of an object to any change in its motion. This is essential for FIRED as it asserts that these systems can continue operation and exhibit a tolerance to missed events, either by design or due to faults.

* Environment can be observed. The fact that CPSs can observe their environment using sensors is fundamental in their design and operation. The inclusion of sensors also means that any actuation of the system can be observed by the sensors. This further implies that the state of the system that caused the actuation can be relearned by the sensors. Roughly speaking this is the same as storing the state of the system (before actuation) to a data store outside the system (the environment), and then reading it back to the system (through the sensors). This feature is critical for FIRED as it allows for certain state to be discarded from the system during resets, i.e., transmitted out of the system before a reset, and re-observed once out of reset. The quality of state may be degraded in this process but as we will see next, CPSs are, by design, resilient to modest degradation.

* Imperfections are tolerable. The physical quantities that need to be sensed are continuous where as digital systems are discrete. This mismatch requires conversion from continuous data to discrete data which introduces quantization error - as a concrete example, while quantities such as pressure, temperature etc. can in theory have infinite precision, the precision of the readings is limited by the analog-to-digital converter found in these sensors which is typically 8-12 bits. Thus the inputs to a CPS are approximations of the real world. Furthermore, sensors also have accuracy problems as the sensing mechanism can (and does) provide a different response depending on environmental conditions, not all of which can be completely characterized. Also, physical artifacts in the environment (such as flying close to an electric line) can perturb sensors. As a result, algorithms and hardware of a CPS are typically designed to account for modest levels of uncertainty. Thus, these systems include multiple sensors from which physical world measurements can be estimated. Furthermore, the algorithms are capable of self-correction. As we will see later this property will allow FIRED to operate smoothly.

3 Adversary Model

* Attack Surfaces: The emerging CPS model considered in this paper has three attack surfaces:

  1. **Sensors & Actuators:** The CPS’s interface to the physical world through sensors and actuators. This is susceptible to physical threats such as tampering of sensors and/or actuators, sensor spoofing and jamming.

  2. **Software:** The control software that handles incoming queries, processes sensor data, and computes actuator commands. This is susceptible to the more traditional software threats such as those stemming from memory vulnerabilities, integer overflows, etc.

  3. **Network:** The network that connects the various components to the controller. This is susceptible to threats such as man-in-the-middle type attacks.

For this work, we consider an adversary that seeks to exploit the control software for these CPSs. We point out that physical-subsystem attacks may serve as entry points to exploit the control software.

* Physical-subsystem Attacks:** Physical attacks typically target state estimation and control; in fact, much work has been done on this front. Attacks on state estimation usually manifest themselves in one of two ways: sensor spoofing and sensor jamming. The difference between these two threats is effectively in the level of control that can be exerted over the sensor, with spoofing being more sophisticated than jamming. Examples of these works are presented by Kerns et al. [19] where they spoof GPS signals to capture and control unmanned aircraft, Davidson et al. [13] who describe how to spoof optical flow sensors in quadcopters, Kune et al. [23] that
present how electromagnetic interference can be used to attack sensors, and Son et al. [33] which incapacitates a drone’s gyroscopes by using intentional noise. It is also important to note that while these attacks are physical in nature, they can affect the cyber component of the system or provide the opportunity for certain cyber attacks to become effective. Also, jamming and spoofing attacks require a degree of spatial proximity: the jamming or spoofing device needs to keep up with the motion of the CPS for continued action.

Cyber-subsystem Attacks: Attacks in the cyber portion of a CPS are essentially the same as those seen on more traditional systems. For example, memory vulnerabilities, such as code reuse and data corruption, are as much a problem for CPS as for other systems. Work by Checkoway et al. [10] and Koscher et al. [22] provide a CPS specific discussion on some of these threats. As discussed above, physical threats can indirectly trigger certain cyber vulnerabilities, for example, integer overflows and underflows. Maliciously manipulated sensor values can cause incorrect branches to be executed in the control algorithms, or worse trigger CPU specific vulnerabilities such as those discussed by Rosenberg [29] for the ARM TrustZone.

Goals and Capabilities: We make specific assumptions about an adversary’s capabilities.

Attacker’s intention is to gain a persistent foothold into the system. Achieving persistence involves compromising at least one of the controllers available. By gaining a persistent foothold, an adversary can hijack the targeted system and attack at a time and place of their choosing. In other words, an attacker’s immediate objective is to sacrifice the integrity of the system. Prior work has considered availability attacks [30] and the defenses provided here are orthogonal to prior defenses.

An attacker will avoid causing irreversible harm to the system. Since an attacker’s objective is to persist in the system any reversible damage may compromise their goals. As a result, an attacker will avoid inducing fatal failure modes (i.e. destruction of the system).

An attacker has complete knowledge of the system internals. The physics of the system and the control algorithms used are known to the attacker.

An attacker’s sphere of influence is bounded. For physical sensor threats an adversary is usually assumed to have access to the physical medium used by the sensor. However, they may not always be within proximity; they may be limited by their equipment or other environmental factors. Similarly, an attacker may be temporally limited.

All these assumptions correspond to stronger adversaries and realities of CPS attacks.

4 FIRED

FIRED is a defensive security technique tailored for CPSs. It combines two orthogonal, but complementary techniques: reset and diversification. This combination in conjunction with the unique properties of CPSs, play off each other to provide stronger security than either technique on its own. We discuss the intuition behind FIRED below.

Why Reset? FIRED takes advantage of a simple and universally applicable panacea for software problems, resetting. Even among expert users, a reset is the preferred solution for nearly any problem in the computing world. The simple intuition behind the effectiveness of this approach is that software is tested most often in its pristine, fresh state as discussed by Oppenheimer et al. [25] and Ding [14]. With respect to the overall health of the system, the conditions of a reset provide a predictable and well defined behavior.

From the viewpoint of thwarting an attacker, the restoration of state, whether it be code, data, or configuration typically helps prevent an attacker’s ability to corrupt the system. For example, simple resets can remove the effects of non persistent attacks that live in memory. More sophisticated reset mechanisms that may restore code or other information, could protect against persistent threats. By frequently performing resets, FIRED limits the effects an attack might have, as well as, the time an attack has to complete. In other words, an attack has a bounded time horizon over which it can affect the system, simply because its effects are frequently removed.

Why Diversify? Typically, once a vulnerability is identified, an adversary can continuously carry out an attack as long as the vulnerability remains present. To remedy this, some variability must be introduced into the system. Otherwise, the same vulnerability would persist. System diversification introduces randomness to prevent the system from being compromised by the same method continuously. The benefits of such an approach have been shown to be successful in a number of related works. As a consequence of diversification, FIRED is able to lower the adversary’s chance of success.

Why Reset & Diversify? In combination, these techniques provide two main advantages:

The first advantage is that diversification can help protect data that needs to be carried across resets. Some CPSs may require certain data that cannot be re-learned during normal operation. For example, sensor calibration data of a quadcopter can only be obtained while it is not in flight. Therefore, it must preserved across resets. One mechanism to protect such data is to take advantage of diversification. Diversification can be used to change the location of the data on every reset, making it harder
for an adversary to locate this persisted data. Another mechanism is encryption. Alternatively, the diversification strategy may encrypt the data with a rotating key that is changed on every reset, making it more difficult to corrupt the data.

The second advantage is that resets can simplify the implementation of certain diversification strategies. For example, re-diversification on traditional systems is typically managed in the following two ways. One way involves running a shadow copy of the program. The shadow copy is diversified in memory and then swapped in with the original program. This technique works well for applications such as RESTful—stateless–APIs, because state information does not need to be shared between the copies. Another diversification mechanism involves a technique known as taint-tracking that allows pointers and other data structures to be tracked during execution. Taint-tracking allows for application state to be migrated between diversified copies of the program. Both of these techniques add a significant level of complexity in order to achieve re-diversification. This additional complexity may make it impractical or impossible to do on certain types of CPSs where resources (e.g. RAM) may be limited. With FIRED, the combination of resets an diversification can help obtain similar results with less complexity. Since resets bring the program to a known point and the majority of the application state is discarded, the amount of pointers or other similar data structures that need to be migrated is significantly reduced. FIRED can simply re-diversify and restart execution.

**Why does this work for CPS?** As discussed in Section 2, CPSs have unique properties. We can rely on inertia to survive resets—the system continues operating during a reset even while missing events. We can also rely on the system’s observability to re-learn about state of the system, and on tolerance to recover from a reset without any intervention. These properties allow us to exploit certain benefits that make tasks such as diversification and resets simpler and practical for resource limited CPSs.

These scenarios can prove difficult to adapt to traditional IT systems as they do not necessarily share these properties. Traditional systems would potentially rely on replication to emulate some of the benefits of inertia. This replication is usually done at the cost of additional memory or hardware. To account for the lack in observability, traditional systems might require a secure data store or some external entity from which to recover it’s state.

**What parameters can we tune?** We consider FIRED to have three distinct modes of operation based on when it chooses to employ reset:

- **Periodic Mode** – The interval between resets is fixed.
- **Random Mode** – The interval between resets is randomly picked from a predetermined range that is considered to be safe.
- **Adaptive Mode** – The interval between resets is dependent on a certain set of criteria. In this mode the system or an observer monitors the effects of a reset and selectively chooses when to execute the reset. These criteria are covered in the safety analysis in Section 5.2.

These modes of operation have their own security strengths and weaknesses. Another parameter to tune is the diversification strategy. Although FIRED does not specify a particular diversification strategy, proper selection impacts the strength of FIRED. Analysis on these topics are provided in Section 5.

## 5 FIRED Analysis

In this section we take a closer look at analyzing FIRED specifically with respect to its security and safety. For the analysis of FIRED, we first consider the periodic mode and then expand the arguments to other modes.

### 5.1 Security

**How does the platform affect security?** For microcontroller-based CPSs, the platform alone can impose certain limitations on the attacker’s capabilities especially when considering the time bound imposed by frequent resets. To achieve persistence on these devices...
that normally execute from Flash, an attacker has two options: (1) copy the contents of a flash sector(s) to RAM, modify the contents in memory, erase the sector(s), and finally write the contents of memory back to flash. (2) Toggle '1' bits to '0' bits in place on flash to modify the contents.

The steps taken for option 1 take a significant amount of time. To give some context, the microcontroller used in our case studies have flash whose smallest sector size is 16KB. Erasing this 16KB sector takes approximately 210ms and writing (the “program” operation) takes around 460ms. If FIRED is able to reset quickly enough, an attacker’s attempt to achieve persistence can be thwarted. An attacker may use option 2, i.e., clear all bits to 0 for individual sectors, to reduce these delays to just the program phase. However, this option is significantly limited. To understand why, let us say the attacker wants to change code or data. The only option they have is to change all of the bits to 0. For instance, if an instruction is set a jump to 0x4000. By writing to the sector an attacker can change the jump to 0x0000. This is usually an illegal address that causes a memory fault. Further, all other instructions would be changed to 0x00 in the adjacent bytes. The same applies to data pages (which need to be programmed for 64KB or larger). So while option 2 may be useful to construct certain portions of an exploit, it is highly restrictive and unlikely to be general-purpose. In fact, the only known microcontroller rootkit [16] does not use the second option.

How are different attack categories affected? We discuss timeliness more concretely by analyzing the probability of an adversary’s success and where FIRED fits in. Attacks generally fall within two separate categories represented by their respective probability functions. The first category, shown in Figure 2, describes an attack that until some condition is met has zero chance of success. This probability function models a memory disclosure attack in which a certain portion of memory must be harvested before the attacker has a chance to hijack the system. Published works describing these types of attacks report that they require a substantial amount of time. If the time to harvest memory is longer than the reset interval, then FIRED successfully defends against the adversary. The second category, shown in Figure 3, describes an attack that over time, slowly becomes more and more likely to succeed as they exhaust their search space. This probability function models a guessing attempt to find the location of core data structures on a system without FIRED, where given enough time an attacker can eventually hijack the system. Because FIRED bounds the duration of an attack, it essentially restricts the probability of hijack. As long as the reset interval \( T_R \) is short enough, then the probability of attack success should remain well below one. For both of these attack categories, diversification seeks to ensure that the attacker’s previous attempts are invalidated and therefore the probability of attack success remains close to 0.

What known attacks can FIRED protect against? We will discuss two concrete attacks and how FIRED provides protection. The first are rootkits. The body of published rootkits for microcontrollers is limited. However, Travis Goodspeed has done significant work exploring the area developing rootkits for the MSP430 microcontroller [16]. The rootkit achieves persistence by writing its payload to flash. Had the system with the MSP430 been reset frequently enough, it might have prevented the rootkit.

A second example of a threat which FIRED can provide relief are defeat devices. These defeat devices have been recently brought into the spotlight after the Volkswagen incident. These devices gather data over time for a variety of parameters such as engine runtime and wheel rotation. They then determine how they should modify their behavior according to whether they are being inspected or not. Because FIRED’s resets essentially clear the data that these ECUs are capturing, it can prevent them from determining the conditions of an emissions test. Of course if the adversary knew about the resets they may engineer more clever defeat devices.

What are appropriate diversification techniques? FIRED does not specify the diversification technique that must be used. Because CPS applications have tight timing requirements, a diversification technique appropriate for one system may not be applicable for the other. Furthermore, resource constraints of a particular system may limit that techniques can be implemented. An example of an applicable diversification strategy candidate relies on execution path randomization similar to Isomeron [12]. Such a strategy can be implemented at compile time with limited runtime support making it appropriate for embedded devices. A compile time Isomeron variant can additionally support resets. For example, a snapshot of RAM state can be restored from a known point without the need of patching addresses, or other variables as the execution of the program still remains diversified.

5.2 Safety

The goal of this section is to develop a framework for when FIRED can be applied to CPSs safely. To do so, we (1) describe how safety requirements are determined, (2) determine what conditions are necessary to fulfill the requirements, and (3) define a set of parameters to relate the effects of FIRED on safety.

From Figure 4, the time which the system needs to recover from one reset should be a sum of the downtime of the system where no output is generated (\( d_R \)) and the time the system needs to stabilize (\( d_S \)). This is due to
The system designer’s only practical option is to tweak parameters as follows:

\[
D = \frac{d_{SS}}{(d_R + d_S)}
\]

Time spent in the stable state pushes the system into a safe region, where as, time spent in recovery is time in which the system is not producing outputs. As a result, the higher the ratio \( D \), the safer and more performant the system can be considered. Given that the downtime \( d_R \) and the time until the first output \( d_S \) are hard to control, the system designer’s only practical option is to tweak the duration of being in the stable state \( d_{SS} \). The ratio \( D \) is used in Section 7 for our evaluation of safety.

**How do the operation modes satisfy safety?** The three modes of operation each affect safety differently. The Periodic and Random modes, provide similar performance to the original system given that \( T_R \) is chosen appropriately. As \( T_R \) decreases past some threshold determined by the minimum time in the stable state, \( d_{SS} \), the system stops functioning correctly. The key for these modes is to provide the minimum \( T_R \) while still providing comparable safety to the system without FIRED. The benefit for these approaches is their simplicity, especially in terms of implementation.

The adaptive strategy can provide the closest performance to the normal system by continuously monitoring its effects and is specifically meant to address safety level S2. If FIRED considers that its actions will violate any of the safety requirements, \( T_R \) can be continuously vary between an upper and lower bound. The difficulty with this strategy is determining the appropriate metric to monitor which varies from system to system.

**How do we include diversification?** While FIRED does not define a particular diversification strategy, one feature they all have in common is increased work. This can result in additional delays compared to the baseline system. In order to satisfy the safety requirements, the additional overhead introduced by diversification should still satisfy the original deadlines. Formally, determining the satisfiability of these timings is done by scheduling analysis. Difficulties in accurately modeling the system make this approach complex leading to experimentation in practice. Due to the highly specific nature of safety, further in depth discussion on the subject is presented when evaluating our case studies in Section 7. For this evaluation, we will demonstrate appropriate safety requirements and explore the limits of the reset interval \( T_R \).

### 6 FIRED Implementation

In order to evaluate FIRED we study two distinct CPSs: an Engine Control Unit (ECU) and a UAV flight controller (FC). Each case study provides its own challenges to determining the feasibility of FIRED, because each case is different with respect to the physical component under control.

#### 6.1 Engine Control Unit

An ECU is the brain of an engine, designed to directly process inputs from a series of sensors and supply output signals to actuators to control the process of internal combustion. As is common to CPSs, an ECU must perform a set of real-time tasks for the engine to perform properly. For a combustion engine to produce the right amount of power, it must inject fuel into its internal chamber, mix it with air, and finally ignite the air-fuel mixture, all at the right timings. Typical engines perform these steps in what is called the four-stroke cycle.

**How it works:** There are two rotating parts, the crank and camshaft, inside an engine. The ECU observes their revolutions to determine what the state of the engine is.
The number of input signals that must be observed to correctly determine the engine state depends on the shapes of the crank and camshaft. Then, the control algorithm interpolates the time to properly schedule ignition and injection events. Once the ECU has determined in which phase of the combustion cycle the engine is in, it will use other measurements from sensors, such as throttle position, temperature, pressure, air-flow and oxygen to accurately determine the air-fuel mixture to be injected.

Platform: For our case study we use the rusEFI open-source ECU and a Honda CBR600RR engine, a very commonly engine used by FSAE racing enthusiasts. The source-code is written in C/C++ running on top of an open-source real-time library operating system called ChibiOS and is designed to run on a STM32F4-Discovery board, a widely popular micro-control unit (MCU). This board contains a 168 MHz ARM Cortex-M4 processor with 192 KBytes of SRAM and 1MB of non-volatile flash memory. The MCU contains only a Memory Protection Unit (MPU) with 8 protection regions, which may be leveraged by diversification techniques.

Reset Strategy: Realizing FIRED involves selecting an appropriate reset strategy. For the ECU, we choose to power cycle the MCU, which effectively clears out all hardware state. Simple power cycling, or reboots, provide strong security advantages as it can be triggered externally, without any software. Additionally, it protects against attacks which may freeze the configuration of certain hardware peripherals. Power cycling incurs certain costs, specifically the cost of rebooting the chip and the time for the startup routines to reinitialize the controller. However, we found that the cost of rebooting the chip was on the order of microseconds and thus completely inconsequential compared to the latency of the startup routine. The non-interactive version of rusEFI’s startup time was 20ms ($d_R = 20ms$.) This is still very fast compared to Desktop systems.

Diversification Strategy: We implement a static variant of Isomeron that provides execution path randomization. The original implementation of Isomeron uses dynamic binary instrumentation techniques. This approach is not feasible on resource constrained devices. By leveraging existing BinUtils functionality compiler flags, our implementation makes it suitable for our targeted devices.

6.2 Flight Controller

Similar to the ECU, the flight controller is the brain of an aircraft and is designed to ensure its stability and control. An aircraft has six degrees of freedom: translation along the $x$, $y$, $z$ directions and rotation about the $x$, $y$, $z$ axes. Each rotational axis is commonly referred to as pitch, roll, yaw, respectively, while the three together are referred to as the attitude. Proper attitude control of the aircraft is critical for its stability.

How it works: The flight controller is primarily responsible for ensuring attitude stability while aiding a pilot or performing autonomous flight. It must read all of the sensor data and filter the noise in order to calculate proper output commands to send to its actuators. In particular, we focus on quadrotor helicopters more commonly referred to as quadcopters. Controlling these quadcopters involves operating four independent rotors to provide six degrees of freedom. Sensors measuring a number of physical properties are then fused together to estimate the position and attitude of the quadcopter. This estimation, similar to the case of ECU, require a certain number of observation samples before an output is produced. This output is then used by other components that determine the best command actions for the system.

Platform: For our case study we use the PX4 open-source flight controller with a DJI F450 quadcopter airframe, a very common DIY kit favored by enthusiasts. The PX4 flight controller provides attitude and position control using a series of sensors such as GPS, optical flow, accelerometer, gyroscope, and barometer. The PX4 controller software includes a variety of flight modes ranging from manual, assisted, to fully autonomous. The source-code is written in C/C++ and supports multiple kinds of OS and hardware targets. Specifically, we use the Pixhawk board based on the same series of MCU as that used in the ECU case study. The overall PX4 architecture uses two main estimators corresponding to the six degrees of freedom: position estimator and attitude estimator. The estimated values are passed to the position controller and attitude controller which are then used to compute the optimal trajectory and trust vectors for the quadcopter. The thrust vectors are then converted from their normalized state to their raw (PWM—pulse-width modulation) values by a mixer and the result is directly supplied to the actuators. Depending on the flight mode, certain components function differently. For assisted mode, pilot inputs are fed directly to the attitude controller to control the quadcopter, while for autonomous mode the system is controlled by a navigator which feeds coordinates to the position control.

Reset Strategy: Similar to the ECU case study, we first attempted simple reboots. The reboot time $d_R$ for PX4 was found to be around 1.5s. Given the more sensitive physical dynamics of the quadcopter, simple rebooting is not effective, i.e., the quadcopter crashed very often, prompting the need of a more efficient approach. As a result, we implement an optimized reset strategy. We found that much of the startup time was spent in initializing data structures and setting up the system for operation. So, we create a snapshot right after all the initial-
ization and use it to practically instantly start the system. This provides certain security benefits as the snapshot can be verified and signed, limiting, or even completely eliminating the possibility of tampering from an attack.

This reset strategy takes a snapshot of the entirety of RAM. It is then stored in a special region of flash and at the following boot, the saved state is restored. The special flash region is protected, and locked by the MPU. This provides a consistent restoration point for the system’s lifetime. This reset strategy was implemented as an extension of the NuttX library operating system used by the Pixhawk PX4 target. This approach takes approximately 3ms (i.e. $d_R = 3\text{ms}$) to restore and is primarily dominated by the time required to write data from flash to RAM.

When the snapshot is taken, and what data is stored in the snapshot, have implications on the capabilities of the system. Depending on the flight mode for the quadcopter the snapshot has different requirements as to what data can be reset and persisted. For the autonomous flight mode for example, coordinates for the quadcopter’s flight path can be part of the snapshot. However, this would prevent the quadcopter’s flight path from being modified mid-flight. If this capability is desired, the said data would need to be persisted across resets. The assisted flight mode has fewer limitations. For the assisted flight mode, which only requires the pilot inputs, a simple snapshot of the system taken after the sensors have been calibrated is sufficient, as the system can recover the state that it needs by reobserving the environment through its sensors.

We found that regardless of the flight mode being used, the snapshot could be taken once in a controlled and secure environment, as long as, the system was initialized with the correct parameters. For the assisted mode this meant, the sensors need to be calibrated, and for the more advanced autonomous mode, mission waypoints for navigation need to be initialized with absolute values as relative measurements become a problem unless they are designed to be persisted. Neither method degraded the quality of the flight.

**Diversification Strategy:** For the flight controller we chose to implement an alternate diversification strategy to show the flexibility of FIRED. We use a simpler randomized stack canary strategy. On each reset, we basically randomly generate a new canary.

## 7 Evaluation

The most critical component of FIRED is resets. We require careful evaluation of its effects on systems. The main questions we study are: what is the frequency of reset at which the system becomes unsafe (a) for the ECU and (b) for the flight controller. Similarly, we also study how the stability of the system is impacted for different frequency modes. In terms of the parameters setup in an earlier Section 5, we will quantify $d_R$, the reset downtime, and what factors affect it, as well as, determine realistic values for the reset interval $T_R$. Fundamentally, $d_R$ value is determined by the reset strategy used while $T_R$ is dependent on the system physics.

**Engine Control Unit:** The reset time of our ECU is 20ms ($d_R = 20\text{ms}$). The stabilization time $d_S$ for the ECU is dependent on the number of engine cycles that must be observed. The ECU must observe two engine cycles to determine whether it is synchronized with the engine’s rotation. Additionally, it must observe enough engine cycles to compute properties that must be integrated over time (e.g., acceleration requires three engine cycles). Assuming an engine speed of 4500RPM (i.e., approx 75Hz), each engine cycle takes 13ms, therefore $d_S \approx 39\text{ms}$.

**Diversification:** For the ECU we studied the effects of our Isomeron implementation. The results showed our version introduced a constant slow down of approximately 2.13x, primarily due to its use of a hardware random number generator. While this slow down may seem large, the original application had more than sufficient slack to accommodate. To put into perspective, even with the slow down, our ECU was still within typical timing accuracy of commercial systems. We found that diversification on the engine had no observable effect.

**Safety Requirements:** In order to validate the safety of the system, we must define feasible safety requirements. We define two such requirements: (1) The engine should maintain its speed (i.e. 4500 RPM or 75 Hz). (2) The engine should not stop.

We performed a set of experiments on a real engine to explore the cost of reset as measured by the drop in engine speed, and how it varies with different reset periods ($T_R$) and reset downtimes ($d_R$). To determine the satisfiability of the first requirement, a sweep of $d_R$ and $T_R$ are performed given a nominal engine speed of 4500RPM.
Figure 5 shows the change in engine speed as a percentage for the sweep. Each line in the graph represents a different reset interval $T_R$. We plot 1s, 500ms, 250ms, 125ms, and 62.5ms reboots. From Figure 5 we can see that the first requirement, maintaining the engine speed, can be satisfied for a wide range of $d_R$ and $f_R$ where the engine speed is approximately 100%.

The second requirement, keeping the engine from stopping, involves the ratio ($D$) of the time the engine spends in its stable state (igniting and injecting fuel) and the time it spends resetting. We observe that as the ratio $D$ decreases for a fixed $T_R$, the engine speed decreases. At some point, depending on the ratio $D$, the ECU is not able to generate enough energy to overcome friction, and the engine comes to a stop, in which case the safety is violated. We refer to the specific engine speed at which this failure occurs as the stopping threshold or the minimum $d_R$. As we reboot more frequently, we observe lower engine speeds without crossing the stopping threshold during operation. We also note that the actual stall threshold varies non-linearly with $T_R$ and $d_R$, most likely due to environmental factors and the large variability in the internal combustion process.

For our experiments, we can therefore conclude that there are specific combinations of reset periods and reset downtimes for which safety can be satisfied even as the system misses events. We further realize that perhaps the most important factor is the ratio $D$ as a result of the difference in time scales between resets and physical actuation.

**Flight Controller:** The reset strategy implemented for the Flight Controller takes approximately 3ms to restore the snapshot (i.e. $d_R$ is 3ms). We will perform the rest of the evaluation with this approach in mind.

**Diversification:** Similar to the ECU, we sought to observe any difference in the system’s behavior introduced by diversification. Our simple strategy in the case of the quadcopter, had a negligible effect.

**Safety Requirements:** Determining appropriate safety requirements for the quadcopter is different from the ECU as different flight modes may call for different requirements. Similar to the ECU, we define two safety requirements for our evaluation: (1) The quadcopter should not oscillate during flight. In other words, its attitude should be stable. (2) The quadcopter must not crash and fall out of the sky.

These two requirements are critical to the safety of the quadcopter as oscillations limit the control and stability of the system, especially when attempting to hover. Additionally, if the quadcopter falls out of the sky, then it could cause irreparable damage to itself and others.

To better gauge the threshold at which a pilot would begin to detect these oscillations, or in other words, the lower limit for $T_R$, we conducted a survey among a set of 20 students. The survey was conducted using an ABX test methodology where various videos of the quadcopter with FIRED during flight for different $T_R$ were shown. Before conducting the survey, users were shown an example video of a stable and unstable flight. They were then shown videos in a random sequence and asked to determine whether there were any observable oscillations during hover flight. The results are shown in Figure 6 indicating that oscillations become significantly observable somewhere between $T_R$ of one-half and one second.

Next, we relate the results of the poll to technical parameters of flight, specifically the attitude. We mounted two Pixhawk flight controllers on the quadcopter: one for control and the other data acquisition to address the limitations as discussed in Section 8. To quantify the effects of Reset, the standard deviation of the quadcopter’s attitude rate over time from the flight data used in the polls was used. The results are shown in Figure 7. The results show little impact on the attitude for $T_R > 1$s and a large spike for smaller values. This indicates that for $T_R > 1$s the stability of the system is roughly equivalent to the system without FIRED and thus safety is maintained. At lower $T_R$ periods, we see a large spike in the standard deviations, which correspond to when we observe the system to start oscillating.

**Adaptive Mode:** Given the variety of external forces...
Quadcopter Stability During Windy Conditions

(a) The roll of the quadcopter from reset period $T_R$ of 1s (left) to 8s (right) during windy conditions. The dashed vertical line marks the point at which the adaptive mode switches the period between resets ($T_R$).

Figure 8: Adaptive Operation Mode with wind.

(b) The stability of the quadcopter’s attitude during windy conditions. Shows the comparison between baseline and different $T_R$.

Figure 9: Braking Performance for various cars.

A quadcopter may be subject to, it makes sense for this system to consider the Adaptive mode to satisfy safety requirements. This would allow the system to respond to wind, among other external factors. The upper and lower bounds chosen for this mode, will thus determine the minimum and maximum $T_R$. At worst if we assume the wind is constant the system will behave no worse than the lower bound $T_R$. In other words, this case will be equivalent to the Periodic mode at the given $T_R$. In reality since wind is typically varied, due to gusts, the average effective $T_R$ of system should fall somewhere between the upper and lower bounds. To demonstrate this we simulated wind using multiple fans blowing into the path of our quadcopter. We operate the quadcopter at $T_R = 1s$ for half of the time and at $T_R = 8s$ for the other. Given the direction in which our fans were blowing, Figure 8a details the quadcopter’s roll angle as affected by the wind. The dotted line marks the point where the transition from a faster to slower reset period is made. On the left side we see $T_R = 1s$ with high fluctuations while on the right we see $T_R = 8s$. From the results shown in Figure 8a we observe that the adaptive mode’s performance follows closer to the lower bound $T_R = 8s$.

Brake Controller: We evaluate how FIRED would affect the braking distance of a car if deployed on a brake controller. It is arguable what safety level (S1-S3) would apply for a brake controller. We argue that it can be categorized as S1 and thus FIRED applies. Under ideal dry conditions, a car can usually achieve a deceleration of $8m/s^2$. FIRED’s resets ultimately increase the stopping time of the car, resulting in a slower deceleration rate. We consider two pairs of $T_R$ and $d_R$, FIRED 1 and FIRED 2 respectively. For FIRED 1, we assume a reset period ($T_R$) of one second and a reset duration ($d_R$) of 100ms. The effective deceleration in this case is roughly 9% slower or $7.27 (m/s^2)$. For FIRED 2, we assume a $T_R$ of 125ms and $d_R$ of 20ms (the same parameters as the ECU) with an effective deceleration of roughly 13.8% slower or $6.96 (m/s^2)$.

Under normal driving conditions the effects of FIRED are marginal and in fact are less than the margin of variability seen among different cars in Figure 9. Additionally, a driver naturally compensates for this difference in deceleration. It is equivalent to driving in one car of one make versus another. There are ways to compensate for these decreases in deceleration as well. Perhaps the simplest approach is to use tires with better traction.

8 Limitations, Mitigations and Applications

Temporary loss of control unacceptable: In some CPSs even a temporary loss of control due to resets may be unacceptable. Examples of these include airplanes during landing or takeoff. Fortunately, these systems also include multiple replicas for fail safe operation and interleaved resets will solve the problem. The Boeing 787 is an example of system that recently recommended interleaved resets [2] for a safety issue. FIRED is also useful for autonomous vehicles, such as commodity package delivery drones where (a) cost is a concern to include redundant components and (b) temporary loss of control may be acceptable since humans are not in the drones to
experience discomfort.

**Wear & Tear:** FIRED may have miscellaneous effects on CPSs that may not have been observable from our current evaluation metrics. These effects can include additional wear and tear of components for example. It is difficult to say whether FIRED may have long term effects as well. However, after having explored these systems, the physical subsystems are built with ample tolerance margins such that we may never see any effects for the duration of the systems lifetime. For example, the rotors on quadcopters are Brushless DC motors (BLDC). BLDCs rely on electronic commutation as opposed to mechanical commutation and therefore do not suffer from much wear and tear.

**Log operations:** It is possible that some CPSs include logging operations that require writing to Flash. In our model we reset before a write to a flash sector can complete thereby denying permanance. To enable logging the CPS may have to be architected to whitelist certain writes to special write only devices.

**A drip-drip attack:** While we prevent complete reprogramming of any flash sector, it is possible that an adversary perform a partial reprogramming to somehow get the flash memory to hold code or data they want. This type of attack is theoretically possible, but practical issues such as controlling the voltage of the flash, or obtaining enough writes/sectors are likely to hinder the attacker.

9 Related Work

CPS Security can be broadly categorized along four dimensions: the threats covered by the defense, the nature of the defense, suitability of the defense to typical CPS environments, and what specific CPS properties, if any, are used to build defenses. Table 1 presents security techniques relevant to the paper from general security techniques to those specific to CPSs. The references used here, especially for the general-purpose security techniques, are not meant to be exhaustive. These are the most recent and most closely related to FIRED.

**Threat Covered:** Following the duality of the CPS, we categorize the threats covered into two groups: (1) **Cyber**—These attacks target the cyber subsystem. This group are those seen on traditional IT systems. (2) **Physical**—These attacks target the physical subsystem. More specifically, it is those attacks which target sensors and actuators. The general security techniques only focus on cyber attacks whereas CPS specific techniques primary focus is on physical attacks.

**Defense Type:** We categorize the defense types into four groups based when the defensive method is applied (during construction or deployment; and what properties are provided by the defense under attack): (1) **Secure-by-Construction (SBC)**—These defenses focus on preventing the root cause for vulnerabilities. (2) **Detection**—These defenses focus on detecting system exploitation during deployment. Does not involve response to a detected attack. (3) **Graceful Degradation**—These defenses focus on mitigating the malicious effects of an attack to maintain acceptable levels of performance or to prolong the life of the system. (4) **Impersistance**—These defenses focus on denying the attacker an ability to gain a foothold or getting rid of foothold the attacker may have gained.

Off-line techniques (formal methods[21], type safe languages[17], static analysis[35]) are secure-by-construction. These techniques are ideal for low power embedded systems since they do not pose any restrictions at run-time. However, we have not seen wide spread use of these techniques in CPS development yet, except for very critical domains.

On-line security techniques focus on attack detection. While the general security techniques focus on software intrusion detection, the CPS specific techniques focus on detection of attacks on physical interfaces, namely sensors and actuators. FIRED fits this category by making attacks that exceed the reset interval impossible.

Graceful degradation under physical attacks has been an active research area in CPS security. The main idea here is to continue operating, perhaps suboptimally, even under attack. In most of these papers, the threat that is considered is an availability attack, and thus continued operation is synonymous with security. Recently proposed techniques [21][35][15] are approaching a point where non-detectable levels of destruction can only affect the system so slowly that stealthy spoofing attacks will become negligible or can be coped with in practical ways.

Impersistance is one of the crucial aspects in CPS security in that it is almost impossible to re-install the firmware during their operation. Moreover, it is essential for many CPS for recovery be performed without human intervention. One of the closest techniques to FIRED among general security techniques is proactive recovery[9]. Their idea is similar to ours but assumes redundancy (i.e. additional hardware) in place of inertia.

Safety of a reset in the CPS context has been discussed before[5]. In fact, for the sake of safety, most of the CPSs require the ability to survive reset during operation, given that a malicious attack or hardware fault can cause the controller to crash at any time. The novelty of our work in this context is that by leveraging the CPS properties, we can survive resets on systems with no additional hardware.

**Deployment:** CPSs are diverse and so is the computing hardware used for them. While some are as powerful
as servers used in traditional IT systems, many have only limited processing power. In order to evaluate whether a technique can be widely applied to CPS, we consider two items: (1) Microcontroller Target—As an extreme case whether the technique can be deployed, we consider a microcontroller with limited processing power and memory (e.g. Cortex-M based STM32F4-Discovery board[1]) that executes in ROM and has no MMU. (2) No Additional Logic—This means no special hardware is necessary for implementing the technique.

Some of the general techniques cannot be adopted in CPS due to their resource demand. Most CPSs that go through mass production are resource limited due to cost. Thus, it is usually unacceptable to increase the computing resources (e.g. CPU frequency and amount of memory) just for security reasons. On the other hand, the addition of simple components may be acceptable as its impact on cost can be negligible. For example, FIRED can be implemented by using a simple timer whose configuration cannot be altered from software exposed to attacks.

**Use of CPS Properties:** The CPS properties that we focus on are: (1) Inertia—This means that a technique relies on the inertia of the system. (2) Predictability—This means that a technique relies on the fact that motion of the system can be predicted.

There is no general security techniques that leverage these CPS properties while most of CPS specific techniques make use of them. To the best of our knowledge, our work is the first to make use of both inertia and predictability of the physical subsystem.

### 10 Conclusion

It is natural to ask if CPSs are indeed unique, if so, how CPS defenses should be different from general-purpose defenses. This paper provides one answer to this question. We construct a new defense that is only practical on CPSs because of their properties. In contrast to prior work on CPSs, which focus mostly on sensors, our defense is tailored for the cyber portion of the CPS. We show that new, simple to implement, low-resource, and effective defenses are possible if we leverage the unique physical properties of CPS.

We present a new CPS-tailored cyber defense called FIRED that combines reset and diversification. FIRED leverages unique properties of cyber-physical systems such as inertia for its implementation. In a traditional system, frequent resets will degrade the usability of the system. In CPSs, however, the CPS can continue to move and operate even during resets because of the momentum/inertia in the system.

In this paper, we showed that FIRED is an effective practical defense for an engine control unit and a flight
controller. From our experiments, we determine that resets can be triggered frequently, as fast as every 125ms for the ECU and every second for the flight controller, without violating safety requirements.

The security benefits of FIRED are two-fold: (a) the resets deny persistence to the attacker. Each reset wipes all volatile or corrupted state, and any write to persistent, non-volatile storage is denied because resets happen too frequently to complete a write to non-volatile memory (b) resets can be used to amplify the security offered by some diversification techniques.

The results of our work show that resets, which may have been previously thought of as unrealistic due to safety, can indeed be done without violating safety requirements. When applicable, FIRED may be especially useful for emerging unmanned CPSs such as drones.

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**Notes**

1 In a library OS, the application is compiled with a library that provides typical OS functions and hardware abstractions.