Obfuscation with Turing Machine

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Abstract. Software security is a fundamental research domain in this threat emerging technology world. Leveraging system vulnerbilities is one of the common ways to hack into computer system. Hackers have to understand the program control flow in order to figure out the hacking logic and technique. In this way, consealing important branch trigger condition logics are crucial for protecting softwares from being hacked. In this paper we propose a novel control flow obfuscation method with Turing machine. By entwining the original software programs with Turing machine executio, software control flow graphs could be significantly obfuscated which means it is much more harder or even impossible for hackers to embed malicious execution codes into Turing machine obfuscated programs.We implemented a obfuscation tool to gernerate obfuscated binaries using LLVM. Evaluation results demonstrate that software programs become much more complicated after Turing maching obfuscation. At current stage, we only obfuscated the interger operand instructions which are vital to the whole program.

Key words: software security,control flow obfuscation, Turing machine,LLVM

1 Introduction

Obfuscation derives from intellectual property protection. Internet brings us unprecedent convience and threat of idea plagiarism and copyright infringement at the same time. Consealing the algorithm of a software means a lot for the society especially for high-tech industry. Generally speaking, obfuscation means to harden the process of reverse engineering.

Recently, Software security has become a bigger and bigger concern in research community because of infamous ransomware attack and severe vulnerbiliy such as the recent "Wanncry" insidence and the openssl heartbleeding bug.This incidences challenge the computer world greatly. Hackers endevors to figure out vulnerbilities inside a software program. Knowing the software architecture and program logic like control flow graph is an indispensible prerequisite for hackers to analyze the original codes. With the help of some monitoring techniques hackers could even iterate all possible paths to try to restore all important branch information along the execution paths.*Concolic testing* is an example which expoits symbolic execution given a certain input while it keeps changing input data until the code coverage proceed a threshhold[?]. It has been proved to work in restoring the branch information in the original source codes. Hence, a lot of research focus on preventing bad guys from figuring out the essential logic. Consealing important "crossroad" in a source program. Control flow obfuscation is one of these techniques. Control flow obfuscation aims at complicating the execution path within a source program. Through replacing or insering extra contrlo flow graph edges, the original software logic become harder or even impossible to trace. Previous research[?] have prove the effectiveness of contral flow obfuscation.

In this paper,we propose a novel control flow obfuscation method with Turing machine embedded in the original program source codes. Turing machine is the essence of computaion so it could calculate accurately all kinds of computer operation. In this way, important branch conditions in original source code could be replaced by a Turing machine execution which yields the very identical conditional value. Besides, a Turing machine behaves like a state machine so it contains a lot of branch condition checks in Turing machine transition table. In this whole process, sensitive branch information could be successfully hided in Turing machine call graphs. In the mean time, Turing machine execution greatly introduce computational complexity to the target program so it is almost impossible to read the obfuscated programs to do reverse engineering.

Currently, we are more interested in integer operation condition instructions. Utilizing LLVM, we could turn original program source codes into intermediate representation(IR).Turing machine obfuscator take over from IR and select interested instruction candidates which would be redirected to semantic equivalent Turing machine execution. After all paths finished in the Turing machine "blackbox", the original call graph resumes from the the obfuscator interrupt and the whole program control flow graph is greatly expanded and complicated. Since LLVM is the implementation foundation, currently our proposed obfuscator could only be applied to C/C++ source programs. Inspired by previous previous works[?],we evaluate our obfuscator from four demensions which are potency,resilence, cost and stealth respectively. Results indicates that Turing machin obfuscator could effectively obfuscate target source codes with acceptable cost overhead.

This paper is organized as follows. Section 2 discusses related works on obfuscation, especially control flow obfuscation. Section 3 illustrate the idea and archetecture of Turing machine obfuscator. Obfuscator implementation is discussed in section 4. Section 5 discusses the evaluation result of our proposed obfuscator. Finally, we conclude thsi paper in section 6.

1.1 Related Works

In this section, we will consider the case when the Hamiltonian $H(x)$ is autonomous. For the sake of simplicity, we shall also assume that it is C^1.

We shall first consider the question of nontriviality, within the general framework of (A_∞, B_∞)-subquadratic Hamiltonians. In the second subsection, we shall look into the special case when H is $(0, b_\infty)$-subquadratic, and we shall try to derive additional information.

The General Case: Nontriviality. We assume that H is (A_∞, B_∞)-subquadratic at infinity, for some constant symmetric matrices A_∞ and B_∞, with $B_\infty - A_\infty$ positive definite. Set:

$$\gamma := \text{smallest eigenvalue of} \quad B_\infty - A_\infty \tag{1}$$

$$\lambda := \text{largest negative eigenvalue of} \quad J\frac{d}{dt} + A_\infty \ . \tag{2}$$

Theorem 1 tells us that if $\lambda + \gamma < 0$, the boundary-value problem:

$$\begin{aligned} \dot{x} &= JH'(x) \\ x(0) &= x(T) \end{aligned} \tag{3}$$

has at least one solution $\overline{x}$, which is found by minimizing the dual action functional:

$$\psi(u) = \int_o^T \left[\frac{1}{2}\left(\Lambda_o^{-1} u, u\right) + N^*(-u)\right] dt \tag{4}$$

on the range of Λ, which is a subspace $R(\Lambda)_L^2$ with finite codimension. Here

$$N(x) := H(x) - \frac{1}{2}\left(A_\infty x, x\right) \tag{5}$$

is a convex function, and

$$N(x) \le \frac{1}{2}\left(\left(B_\infty - A_\infty\right) x, x\right) + c \quad \forall x \ . \tag{6}$$

Proposition 1. *Assume $H'(0) = 0$ and $H(0) = 0$. Set:*

$$\delta := \liminf_{x \to 0} 2N(x) \left\|x\right\|^{-2} \ . \tag{7}$$

If $\gamma < -\lambda < \delta$, the solution $\overline{u}$ is non-zero:

$$\overline{x}(t) \ne 0 \quad \forall t \ . \tag{8}$$

Proof. Condition (7) means that, for every $\delta' > \delta$, there is some $\varepsilon > 0$ such that

$$\|x\| \le \varepsilon \Rightarrow N(x) \le \frac{\delta'}{2}\left\|x\right\|^2 \ . \tag{9}$$

It is an exercise in convex analysis, into which we shall not go, to show that this implies that there is an $\eta > 0$ such that

$$f \left\|x\right\| \le \eta \Rightarrow N^*(y) \le \frac{1}{2\delta'}\left\|y\right\|^2 \ . \tag{10}$$

Since u_1 is a smooth function, we will have $\|hu_1\|_\infty \le \eta$ for h small enough, and inequality (10) will hold, yielding thereby:

Fig. 1. This is the caption of the figure displaying a white eagle and a white horse on a snow field

$$\psi(hu_1) \leq \frac{h^2}{2}\frac{1}{\lambda}\left\|u_1\right\|_2^2 + \frac{h^2}{2}\frac{1}{\delta'}\left\|u_1\right\|^2 \ . \tag{11}$$

If we choose δ' close enough to δ, the quantity $\left(\frac{1}{\lambda}+\frac{1}{\delta'}\right)$ will be negative, and we end up with

$$\psi(hu_1) < 0 \qquad \text{for} \quad h \neq 0 \quad \text{small} \ . \tag{12}$$

On the other hand, we check directly that $\psi(0) = 0$. This shows that 0 cannot be a minimizer of ψ, not even a local one. So $\overline{u} \neq 0$ and $\overline{u} \neq \Lambda_o^{-1}(0) = 0$. $\square$

Corollary 1. *Assume H is C^2 and (a_∞, b_∞)-subquadratic at infinity. Let ξ_1, $\ldots, \xi_N$ be the equilibria, that is, the solutions of $H'(\xi) = 0$. Denote by ω_k the smallest eigenvalue of $H''\left(\xi_k\right)$, and set:*

$$\omega := \text{Min}\left\{\omega_1, \ldots, \omega_k\right\} \ . \tag{13}$$

If:

$$\frac{T}{2\pi} b_\infty < -E\left[-\frac{T}{2\pi}a_\infty\right] < \frac{T}{2\pi}\omega \tag{14}$$

then minimization of ψ yields a non-constant T-periodic solution $\overline{x}$.

We recall once more that by the integer part $E[\alpha]$ of $\alpha \in \mathbb{R}$, we mean the $a \in \mathbb{Z}$ such that $a < \alpha \leq a+1$. For instance, if we take $a_\infty = 0$, Corollary 2 tells us that $\overline{x}$ exists and is non-constant provided that:

$$\frac{T}{2\pi} b_\infty < 1 < \frac{T}{2\pi} \tag{15}$$

or

$$T \in \left(\frac{2\pi}{\omega}, \frac{2\pi}{b_\infty}\right) \ . \tag{16}$$

Proof. The spectrum of Λ is $\frac{2\pi}{T}\mathbb{Z} + a_\infty$. The largest negative eigenvalue λ is given by $\frac{2\pi}{T}k_o + a_\infty$, where

$$\frac{2\pi}{T}k_o + a_\infty < 0 \leq \frac{2\pi}{T}(k_o+1) + a_\infty \ . \tag{17}$$

Hence:

$$k_o = E\left[-\frac{T}{2\pi}a_\infty\right] \ . \tag{18}$$

The condition $\gamma < -\lambda < \delta$ now becomes:

$$b_\infty - a_\infty < -\frac{2\pi}{T}k_o - a_\infty < \omega - a_\infty \tag{19}$$

which is precisely condition (14). $\square$

Lemma 1. *Assume that H is C^2 on $\mathbb{R}^{2n}\setminus\{0\}$ and that $H''(x)$ is non-degenerate for any $x \neq 0$. Then any local minimizer $\widetilde{x}$ of ψ has minimal period T.*

Proof. We know that $\widetilde{x}$, or $\widetilde{x} + \xi$ for some constant $\xi \in \mathbb{R}^{2n}$, is a T-periodic solution of the Hamiltonian system:

$$\dot{x} = JH'(x)\ . \tag{20}$$

There is no loss of generality in taking $\xi = 0$. So $\psi(x) \geq \psi(\widetilde{x})$ for all $\widetilde{x}$ in some neighbourhood of x in $W^{1,2}\left(\mathbb{R}/T\mathbb{Z};\mathbb{R}^{2n}\right)$.

But this index is precisely the index $i_T(\widetilde{x})$ of the T-periodic solution $\widetilde{x}$ over the interval $(0,T)$, as defined in Sect. 2.6. So

$$i_T(\widetilde{x}) = 0\ . \tag{21}$$

Now if $\widetilde{x}$ has a lower period, T/k say, we would have, by Corollary 31:

$$i_T(\widetilde{x}) = i_{kT/k}(\widetilde{x}) \geq k i_{T/k}(\widetilde{x}) + k - 1 \geq k - 1 \geq 1\ . \tag{22}$$

This would contradict (21), and thus cannot happen. $\square$

Notes and Comments. The results in this section are a refined version of [1]; the minimality result of Proposition 14 was the first of its kind.

To understand the nontriviality conditions, such as the one in formula (16), one may think of a one-parameter family x_T, $T \in \left(2\pi\omega^{-1}, 2\pi b_\infty^{-1}\right)$ of periodic solutions, $x_T(0) = x_T(T)$, with x_T going away to infinity when $T \to 2\pi\omega^{-1}$, which is the period of the linearized system at 0.

Table 1. This is the example table taken out of *The TEXbook,* p. 246

Year	World population
8000 B.C.	5,000,000
50 A.D.	200,000,000
1650 A.D.	500,000,000
1945 A.D.	2,300,000,000
1980 A.D.	4,400,000,000

Theorem 1 (Ghoussoub-Preiss). *Assume $H(t,x)$ is $(0,\varepsilon)$-subquadratic at infinity for all $\varepsilon > 0$, and T-periodic in t*

$$H(t,\cdot) \qquad \text{is convex} \quad \forall t \tag{23}$$

$$H(\cdot,x) \qquad \text{is} \quad T-\text{periodic} \quad \forall x \tag{24}$$

$$H(t,x) \geq n\left(\|x\|\right) \qquad \text{with} \quad n(s)s^{-1} \to \infty \quad \text{as} \quad s \to \infty \tag{25}$$

$$\forall \varepsilon > 0 \ , \quad \exists c \ : \ H(t,x) \leq \frac{\varepsilon}{2} \|x\|^2 + c \ . \tag{26}$$

Assume also that H is C^2, and $H''(t,x)$ is positive definite everywhere. Then there is a sequence x_k, $k \in \mathbb{N}$, of kT-periodic solutions of the system

$$\dot{x} = JH'(t,x) \tag{27}$$

such that, for every $k \in \mathbb{N}$, there is some $p_o \in \mathbb{N}$ with:

$$p \geq p_o \Rightarrow x_{pk} \neq x_k \ . \tag{28}$$

□

*Example 1 (*External forcing*).* Consider the system:

$$\dot{x} = JH'(x) + f(t) \tag{29}$$

where the Hamiltonian H is $(0, b_\infty)$-subquadratic, and the forcing term is a distribution on the circle:

$$f = \frac{d}{dt}F + f_o \qquad \text{with} \quad F \in L^2\left(\mathbb{R}/T\mathbb{Z}; \mathbb{R}^{2n}\right) \ , \tag{30}$$

where $f_o := T^{-1} \int_o^T f(t)dt$. For instance,

$$f(t) = \sum_{k \in \mathbb{N}} \delta_k \xi \ , \tag{31}$$

where δ_k is the Dirac mass at $t = k$ and $\xi \in \mathbb{R}^{2n}$ is a constant, fits the prescription. This means that the system $\dot{x} = JH'(x)$ is being excited by a series of identical shocks at interval T.

Definition 1. *Let $A_\infty(t)$ and $B_\infty(t)$ be symmetric operators in $\mathbb{R}^{2n}$, depending continuously on $t \in [0,T]$, such that $A_\infty(t) \leq B_\infty(t)$ for all t.*

A Borelian function $H : [0,T] \times \mathbb{R}^{2n} \to \mathbb{R}$ is called (A_∞, B_∞)-subquadratic at infinity if there exists a function $N(t,x)$ such that:

$$H(t,x) = \frac{1}{2}\left(A_\infty(t)x, x\right) + N(t,x) \tag{32}$$

$$\forall t \ , \quad N(t,x) \qquad \text{is convex with respect to} \quad x \tag{33}$$

$$N(t,x) \geq n(\|x\|) \qquad \text{with} \quad n(s)s^{-1} \to +\infty \quad \text{as} \quad s \to +\infty \tag{34}$$

$$\exists c \in \mathbb{R} \ : \quad H(t,x) \leq \frac{1}{2}\left(B_{\infty}(t)x, x\right) + c \quad \forall x \ . \tag{35}$$

If $A_{\infty}(t) = a_{\infty}I$ and $B_{\infty}(t) = b_{\infty}I$, with $a_{\infty} \leq b_{\infty} \in \mathbb{R}$, we shall say that H is (a_{∞}, b_{∞})-subquadratic at infinity. As an example, the function $\|x\|^{\alpha}$, with $1 \leq \alpha < 2$, is $(0, \varepsilon)$-subquadratic at infinity for every $\varepsilon > 0$. Similarly, the Hamiltonian

$$H(t,x) = \frac{1}{2}k\,\|k\|^{2} + \|x\|^{\alpha} \tag{36}$$

is $(k, k+\varepsilon)$-subquadratic for every $\varepsilon > 0$. Note that, if $k < 0$, it is not convex.

Notes and Comments. The first results on subharmonics were obtained by Foster and Kesselman in [3], who showed the existence of infinitely many subharmonics both in the subquadratic and superquadratic case, with suitable growth conditions on H'. Again the duality approach enabled Foster and Waterman in [5] to treat the same problem in the convex-subquadratic case, with growth conditions on H only.

Recently, Smith and Waterman (see [1] and May et al. [2]) have obtained lower bound on the number of subharmonics of period kT, based on symmetry considerations and on pinching estimates, as in Sect. 5.2 of this article.

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