

EVOLUTIONARY DATA MINING APPROACH TO CREATING DIGITAL LOGIC

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Abstract: A data mining based procedure for automated reverse engineering has been developed. The data mining algorithm for reverse engineering uses a genetic program (GP) as a data mining function. A genetic program is an algorithm based on the theory of evolution that automatically evolves populations of computer programs or mathematical expressions, eventually selecting one that is optimal in the sense it maximizes a measure of effectiveness, referred to as a fitness function. The system to be reverse engineered is typically a sensor. Design documents for the sensor are not available and conditions prevent the sensor from being taken apart. The sensor is used to create a database of input signals and output measurements. Rules about the likely design properties of the sensor are collected from experts. The rules are used to create a fitness function for the genetic program. Genetic program based data mining is then conducted. This procedure incorporates not only the experts' rules into the fitness function, but also the information in the database. The information extracted through this process is the internal design specifications of the sensor. Significant mathematical formalism and experimental results related to GP based data mining for reverse engineering will be provided.

1 INTRODUCTION

An engineer must design a signal that will yield a particular type of output from a sensor device (SD). The engineer does not have design specifications for the sensor system and the machine may not be disassembled or invasively examined. The engineer might attempt to find the correct signal through trial and error, but this would be very time consuming and access to experimental resources is very expensive. To deal with this problem a genetic program (GP) based data mining (DM) procedure has been invented (Smith 2005).

A genetic program is an algorithm based on the theory of evolution that automatically evolves populations of computer programs or mathematical expressions, eventually selecting one that is optimal in the sense it maximizes a measure of effectiveness, referred to as a fitness function (Koza 1999; Smith 2003a, 2003b, 2004). The system to be reverse engineered is typically a sensor. The sensor is used to create a database of input signals and output measurements. Rules about the likely design properties of the sensor are collected from experts.

The rules are used to create a fitness function for the genetic program. Genetic program based data mining is then conducted (Bigus 1996, Smith 2003a, 2003b, 2004). This procedure incorporates not only experts' rules into the fitness function, but also the information in the database. The information extracted through this process is the internal design specifications of the sensor. The design properties extracted through this process can be used to design a signal that will produce a desired output (Smith 2005). Determination of such signals can be essential to ultimate determination of control rules for automatic multiplatform coordination (Smith 2003a, 2003b, 2004).

GPs require a terminal set and function set as inputs. The terminals are the actual variables of the problem. These can include a variable like "x" used as a symbol in building a polynomial and also real constants. The function set consists of a list of functions that can operate on the variables. When a GP was used as a DM function in the past to automatically create fuzzy decision trees, the terminals consisted of fuzzy root concepts and the functions consisted of fuzzy logical connectives and

fuzzy modifiers (Smith 2003a, 2003b, 2004).

When the GP is used as a data mining function, a database of input and output information is required. When the GP is used as a data mining function for evolving digital logic (DL), the database contains inputs to the DL as well as measured outputs. The experts' opinions are manifested in the selection of the input and associated output to be included in the database. For the DL case an additional form of input consisting of "rules" about DL construction are included.

Section 2 discusses data mining and the use of a genetic program as a data mining function. Section 3 examines one of the digital logic designs to be reverse engineered using genetic program based data mining. Section 4 explains the genetic program's terminal set, function set, and fitness function. Section 4 also gives detailed formulations of the rule fitness, fitness score, input-output fitness, and overall fitness. Section 5 provides experimental results with detailed descriptions of the evolutionary properties. Finally, section 6 provides conclusions.

2 GP BASED DATA MINING

Data mining is the efficient extraction of valuable non-obvious information embedded in a large quantity of data (Bigus 1996). Data mining consists of three steps: the construction of a database that represents truth; the calling of the data mining function to extract the valuable information, e.g., a clustering algorithm, neural net, genetic algorithm, genetic program, etc; and finally determining the value of the information extracted in the second step, this generally involves visualization.

When used for reverse engineering, the GP, typically data mines a database to determine a graph-theoretic structure, e.g., a system's DL diagram or an algorithm's flow chart or decision tree (Smith 2003a, 2003b, 2004). The GP mines the information from a database consisting of input and output values, e.g., a set of inputs to a sensor and its measured outputs. GP based data mining will be applied to the construction of the DLs described in sections 3 and 5.

To use the genetic program it is necessary to construct terminal and function sets relevant to the problem. Before the specific terminal and function sets for the reverse engineering problems are described, a more detailed description of one of the digital logic examples to be considered will be given in section 3.

3 DIGITAL LOGIC TO BE REVERSE ENGINEERED

The first DL design to be reverse engineered is given in prefix notation in (1) and is depicted diagrammatically in Figure 1,

$$\begin{aligned}
 &OR2\ OR3DELAY\ AND3\ H_1\ MAX_SIG123\ H_3 \\
 &SUM_SIG2\ H_2\ DIFF\ SUM_SIG2\ SUM_SIG123 \\
 &OR3DELAY\ AND3\ H_1\ MAX_SIG123\ H_3 \\
 &SUM_SIG3\ H_2\ DIFF\ SUM_SIG3\ SUM_SIG123.
 \end{aligned}
 \tag{1}$$

The notation is described in (Smith 2005) and summarized in this section. This DL is not known to the GP. The GP only has access to a database of input signals to the DL and measured output, as well as, a database of rules provided by experts for building the DL.

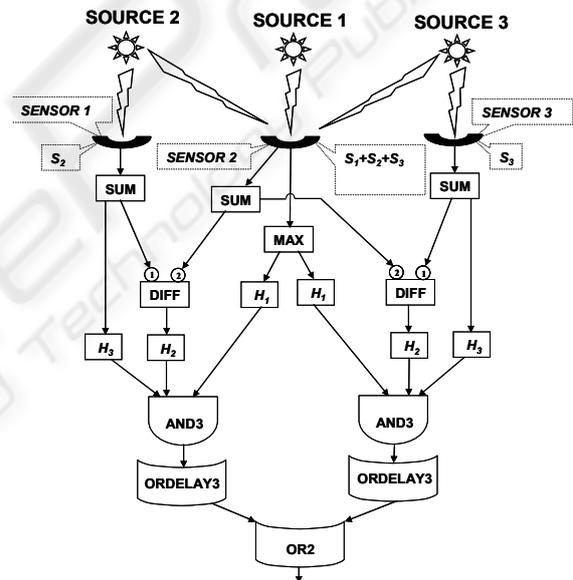


Figure 1: The first DL to be reverse engineered.

The DL consists of three input channels each with a sensor attached. The sensors receive signals from sources one, two and three. Only measurements from the central source in Figure 1 are of interest. Due to the geometry of the sources and properties of the sensors only sensor two can receive emissions from the central source that are significant. Unfortunately, sensor two's measurement may be corrupted by emissions from the other two sources. The digital logic is constructed so that if there were significant corruption of sensor two's measurements, then the final OR-gate returns unity, so the measurements

can be ignored.

There are a number of DL elements that are used repeatedly. The DL components and signals will ultimately become elements of the GP's terminal and function sets. The sensors will receive an analog signal and convert it to a digital form, i.e., they will map real-valued input to the set of integers. A sampling window of size N is used, i.e., the signal is sampled every Δt seconds for a total of N samples in that window. The sample is indicated by the vector \vec{s}_j in (2) with sampling beginning at time t_o . The j -subscript implies the signal originated in the j^{th} source, where $j=1,2,3$,

$$\vec{s}_j = [s_j(t_o), s_j(t_o + \Delta t), \dots, s_j(t_o + (N-1) \cdot \Delta t)]. \quad (2)$$

The DL function, *SUM*, given explicitly in (3), represents the logarithmic sum of the absolute value of the time components of the digitized input that has been received for a single window of length N ,

$$SUM(\vec{s}_j) = \log \left[\sum_{k=1}^N |s_j(t_o + (k-1) \cdot \Delta t)| \right]. \quad (3)$$

The elements labeled H_i , for $i=1,2,3$, are Heaviside step functions as given in (4). If the input is greater than or equal to a threshold, τ_i , for $i=1,2,3$; then a value of unity is transmitted, otherwise a zero is transmitted,

$$H_i(s) = \begin{cases} 1, & \text{if } s \geq \tau_i \\ 0, & \text{if } s < \tau_i \end{cases}. \quad (4)$$

The DL function, *MAX*, given in (5), returns the common logarithm of the maximum absolute value of the time components of the input signal for a single window of length N . The element labeled *DIFF*, takes the difference between input to its first and second arguments as indicated in (5).

$$MAX(\vec{s}_j) = \log \left[\max_{k=1}^N |s_j(t_o + (k-1) \cdot \Delta t)| \right] \quad (5)$$

$$DIFF(I_1, I_2) = I_1 - I_2 \quad (6)$$

The DL function, *OR3DELAY*, takes only Boolean inputs, i.e., it expects zero or one as an input. It waits until it has three consecutive inputs from three consecutive time windows, hence the "3" in its name. Once it receives three consecutive

inputs, it yields as an output the maximum of its inputs. Also not depicted, but used in the GP's function set are *AND3DELAY*, which takes three inputs of zero or one corresponding to three consecutive time windows and yields as output the minimum of its inputs. Finally, the symbols labeled *AND3*, *OR3*, *AND2*, and *OR2* are the conventional logical connectives *AND* and *OR*, with the numerical designation indicating the number of inputs expected, e.g., *AND3* expects three Boolean inputs.

The signals are additive, at any given time sensor two may record a superposition of the three sources' transmissions, which is represented by $s_1(t) + s_2(t) + s_3(t)$. If the three sensors' signals are of sufficient magnitude then this is characteristic of corruption and the final *OR* in Figure 1 returns unity.

4 GP TERMINAL SET, FUNCTION SET AND FITNESS

This section describes the GPs terminal set, function set, and the fitness functions. The description is given in terms of DL elements and properties, but the genetic program based reverse engineering technique is very general and can be applied to any system that can be described in a graph theoretic language, e.g., decision processes described in terms of decision trees (Smith 2003a, 2003b, 2004).

The terminal set consists of the following elements:

$$T = \{SUM_SIG123, MAX_SIG123, SUM_SIG2, MAX_SIG2, SUM_SIG3, MAX_SIG3\}, \quad (7)$$

where

$$SUM_SIG123 = SUM(\vec{s}_1 + \vec{s}_2 + \vec{s}_3), \quad (8)$$

$$MAX_SIG123 = MAX(\vec{s}_1 + \vec{s}_2 + \vec{s}_3), \quad (9)$$

$$SUM_SIG2 = SUM(\vec{s}_2), \quad (10)$$

$$MAX_SIG2 = MAX(\vec{s}_2), \quad (11)$$

$$SUM_SIG3 = SUM(\vec{s}_3), \quad (12)$$

$$MAX_SIG3 = MAX(\vec{s}_3). \quad (13)$$

All sensor measurements begin at time, t_o .

The function set consists of the following

elements:

$$F = \{AND3, OR3, AND2, OR2, AND3DELAY, OR3DELAY, H_1, H_2, H_3, DIFF\}. \quad (14)$$

The function *AND3DELAY* is not used for the DL under consideration. By including it, the GP's ability to discriminate against extraneous functions is emphasized.

The DL design to be evolved by the GP is given in (1). The GP's ability to do this will be determined largely by the fitness function and the underlying databases to be discussed.

As with all GPs there must be a fitness function for evaluation of the evolving population of chromosomes. The fitness function, referred to as the overall fitness (OF) denoted as f_{OF} is actually the sum of two other fitness functions. These functions are the rule fitness (RF) and the input-output fitness (IOF) denoted as f_{RF} and f_{IOF} , respectively. The rule fitness is given in (15) where the indicator function, I_i is unity if the i^{th} rule is satisfied and zero otherwise, and v_i is the value of the i^{th} rule. Table 1 provides a small subset of the 12 rules used.

$$f_{RF} = \sum_{i=1}^{12} I_i \cdot v_i \quad (15)$$

Let DL_j denote the j^{th} element of the evolving population of chromosomes within the GP for $j = 1, 2, \dots, m_{ps}$ where m_{ps} is the population size, i.e., the number of chromosomes. Let each DL_j consists of an OR2 or AND2 that connects two subgraphs, denoted as DL_j_left and DL_j_right . Let $l(DL_j_c)$ be the length, i.e., the number of nodes in DL_j_c , for $c \in \{left, right\}$. If $l(DL_j_c)$ is greater than or equal to 20 then the parsimony pressure, $\alpha_p \cdot l(DL_j_c)$ is subtracted from the rule fitness followed by division by 100, ultimately yielding the rule score, denoted as g_{RS} . This subtraction is done if either $l(DL_j_left)$ or $l(DL_j_right)$ exceeds 20. The quantity α_p is referred to as the parsimony coefficient (Smith 2005). The rule score is expressed compactly as

$$g_{RS}(DL_j) = \frac{1}{100} \{f_{RF}(DL_j_left) - \chi[l(DL_j_left) - 20] \cdot \alpha_p \cdot l(DL_j_left)\} + \frac{1}{100} \{f_{RF}(DL_j_right) - \chi[l(DL_j_right) - 20] \cdot \alpha_p \cdot l(DL_j_right)\}, \quad (16)$$

where the Heaviside step function χ takes the value unity for non-negative arguments and is zero otherwise. If the rule score exceeds the rule threshold denoted as, κ_{RT} then and only then is the input-output fitness evaluated. By forcing the rule score to exceed a threshold before the input-output fitness is evaluated a great deal of computational complexity is avoided.

Let DL^T denote the true digital logic diagram that underlies the SD used to construct the input-output database. For the examples considered in this paper let there be three signals. The input-output database is assumed to have the following structure

$$M_{DB} = \begin{bmatrix} \vec{S}_1^1 & \vec{S}_2^1 & \vec{S}_3^1 & B^1 \\ \vec{S}_1^2 & \vec{S}_2^2 & \vec{S}_3^2 & B^2 \\ \vdots & \vdots & \vdots & \vdots \\ \vec{S}_1^m & \vec{S}_2^m & \vec{S}_3^m & B^m \end{bmatrix}, \quad (17)$$

where \vec{S}_j^k is the three time window input from the j^{th} source for the k^{th} input; $B^k \in \{0, 1\}$ is the k^{th} output from DL^T for $k = 1, 2, \dots, m$, i.e.,

$$B^k = DL^T \left(\vec{S}_1^k, \vec{S}_2^k, \vec{S}_3^k \right); \quad (18) \\ \text{for } k = 1, 2, \dots, m.$$

Table 1: Subset of the rule set for computational GP experiments.

R1: If either <i>OR3DELAY</i> or <i>AND3DELAY</i> are present during rule fitness evaluation add $v_1 = 5$.
R2: If <i>AND3</i> or <i>OR3</i> are present during fitness evaluation add $v_2 = 5$.

The input-output fitness for the j^{th} chromosome, DL_j , is defined as

$$f_{IOF}(j, M_{DB}) = \frac{1}{\left[1 + \sum_{k=1}^m \left| DL_j(\vec{S}_1^k, \vec{S}_2^k, \vec{S}_3^k) - B^k \right|^2 \right]} \quad (19)$$

The overall fitness, f_{OF} , for the j^{th} chromosome can be written as

$$f_{OF}(j, M_{DB}) = g_{RS}(DL_j) + \chi(g_{RS}(DL_j) - \kappa_{RT}) \cdot f_{IOF}(j, M_{DB}). \quad (20)$$

It is important to recall that in actual implementation, the input-output fitness is only evaluated if the rule fitness is greater than or equal to the rule threshold. Selectively evaluating the input-output fitness greatly reduces the computational complexity and hence the run-time of the GP.

5 DATA MINING RESULTS

In this section two different DL schemes data mined by the GP are considered. The two examples presented here are representative of the many experiments that have been conducted to show the effectiveness of the GP based data mining procedure presented in this paper. The first is the DL represented in (1) and also in Figure 1. This DL will assume the value of DL^T for the discussion below. Using various databases too large to reproduce here and different random number generator seeds, the GP was able to reverse engineer (1) in no more than 76 GP generations. The different number of generations and amounts of CPU time required reflects the effect of different input-output databases and also the random number generator seeds. One database may constrain the evolutionary process more than another resulting in fitness values that over time push the population more rapidly toward DL^T . Also, since the initial population is generated randomly; and crossover, mutation, architecture altering steps (Smith 2005) (AAS) and symmetrical replication (Smith 2005) (SR) have random aspects, a change in the seed of the random number generator can also impact run-time.

To get a feel for the evolutionary process it is useful to examine some intermediate generations that lead to DL^T . For the case in which (1) is

reverse engineered in 76 generations the elite chromosomes found for different generations are provided in Table 2 with the 76th generation reproducing the correct chromosome given in (1).

The chromosomes entered into Table 2 reflect some of the characteristics observed during the evolutionary process. From the first generation forward the GP is able to find best candidates that have an *OR2* at the end of the chromosome. The presence of two *DIFF* operators in the first generation is also promising. The best chromosome for the first generation is much too short when compared to the desired result.

New innovations are found in generation 25 in that both arguments of both *DIFFs* use *MAX* functions as well as the *SIG123* structure. Even though it is expected that both arguments will ultimately use *SUM* functions, the use of a common function for both arguments may show evolution in the proper direction. Both *DIFF* operators are preceded by H_2 which is what is found in (1). Even with these innovations the best chromosome of generation 25 is far from the correct result.

All generations after the 26th have elite chromosomes that have underlying graphs isomorphic to the final solution. The GP's effort from generation 27 through 76 involves finding a solution with the proper node labels. Various rows in the input-output (IO) database, i.e., (17) contribute to proper labeling, e.g., if a certain row in the database is deleted then it is likely the final GP solution would not have proper threshold labeling. An improper threshold value is undesirable from the standpoint of trying to reproduce the exact digital logic. If the goal is to produce an input signal that yields unity as an output then even with the threshold value wrong, as long as the input signal has sufficient energy to take into account uncertainty, then the desired output is obtained. In conclusion, the ultimate cost of information uncertainty in this case is a small amount of additional power.

The best chromosome of the 50th generation is far closer to (1). The *MAX* functions in the arguments of the *DIFF* have been replaced by *SUM* functions. The arguments of the *DIFF* operators are the ones for the final result and the output of both *DIFFs* is passed into H_2 as found in (1). In this chromosome replacing H_1 *MAX_SIG2* with H_3 *SUM_SIG2* and H_1 *MAX_SIG3* with H_3 *SUM_SIG3* would yield the correct result. Finally, the desired result is found in generation 76.

For a second example consider the DL given below in (21) as DL^T , i.e., truth,

$$\begin{aligned}
 &OR2\ OR3DELAY\ AND3\ H_1\ SUM_SIG123 \\
 &H_3\ MAX_SIG2\ H_2\ DIFF\ MAX_SIG2 \\
 &MAX_SIG123\ OR3DELAY\ AND3\ H_1 \\
 &SUM_SIG123\ H_3\ MAX_SIG3\ H_2\ DIFF \\
 &MAX_SIG3\ MAX_SIG123.
 \end{aligned} \tag{21}$$

The GP's evolutionary process for inverting (21) is summarized in Table 3.

This example is similar to (1), in fact if in (1) the *MAX* operations are replaced by the *SUM* operation and *SUM* replaced by *MAX*, then (21) is obtained. Given that (1) and (21) only differ in labeling of the underlying graphs it is anticipated that the GP based evolutionary processes that yield (1) and (21) would be similar. This anticipation is born out, but there are differences in the evolutionary processes. One significant difference is that the chromosome in (21) is evolved in a smaller number of generations than the one found in (1). There is nothing that is obvious about the rule set or input-output data based used for both chromosomes that would favor one over the other. Experimentation seems to indicate the difference in the number of generations required is related to the seed of the random number generator.

Just as with the example in Table 2, the best chromosome of the first generation has an *OR2* at the end, but is otherwise too short and far removed from the correct answer. By the eighth generation the "*H₂ DIFF MAX_SIG2 MAX_SIG123*" structure has emerged. The best chromosome of the 16th generation preserves the best features of previous generations and also makes use of an *OR3DELAY*, but it still has many defects. For all generations after the 26th generation the elite chromosome has two subgraphs that take a form that can be derived in closed form. The elite chromosome of the 30th generation has many correct labels and incorrect ones. It illustrates how evolution can fluctuate from generation to generation producing individuals of higher fitness, but departing significantly from the true DL in form. Finally in generation 46 the GP converges having produced the correct DL design.

As referenced above it is possible to derive closed form exact results for the set of digital logic diagrams or set of DL maps referred to as DLS that exactly maximize the rule score. The graph underlying each DL diagram is isomorphic in the graph-theoretic sense to the graph underlying DL^T . Furthermore, for certain signal types it is possible to write down closed form exact results for the image sets under these DL maps. From the image set closed form exact entries for an input-output

database can be derived that maximize the overall fitness.

It is found that by the 26th generation in the computational studies of Tables 2 and 3 that the GP finds a member of DLS. After the 26th generation the GP's elite solutions remain within DLS each generation. The GP spends the rest of the generations until it converges, re-labeling the underlying elite graphs eventually evolving DL^T .

By selectively eliminating rules from the rule set, of which Table 1 is a subset or eliminating rows from the derived IO database, the effect of uncertainty can be studied. The elimination of rules represents an approach to the determining the effect of linguistic imprecision, i.e., the inability of experts to provide crisp rules. The random loss of a row or rows from the IO database provides a model of the effect of uncertainty born of randomness during measurement.

The implications for the two kinds of uncertainty can be significantly different. Loss of a rule or rules can greatly expand the set of DL maps that will maximize the rule-score. If all the rules are maintained, but rows are lost from the IO database, then the ultimate solution can be quite different than truth, but the underlying graph will still be isomorphic to DL^T . In many instances the real effect of loss of rows from the IO database is to interchange thresholds on the resulting DL map. When this occurs input signals can still be designed that will produce a desirable output. The resulting signal will be mathematically similar to the true DL, but more signal power will be required. So the effect of certain kinds of uncertainty is the requirement for more power. So the DL map has an *uncertainty insensitivity* (UI) up to power.

6 SUMMARY AND CONCLUSIONS

Genetic program (GP) based data mining has proven effective for reverse engineering the complex digital logic underlying sensor devices (SDs) when the original design specifications for these devices are unavailable and invasive study of the systems is impossible.

The database that was subjected to data mining consisted of known input to the digital logic (DL), the associated measured output and a set of rules provided by experts relating to their assumptions about the digital logic. It is found that having a set of expert rules in the database is essential; the

Table 2: Evolution of the DL depicted in Figure 1

Generation	Best Chromosome found in the Population for the Indicated Generation
1	OR2 H ₂ DIFF SUM SIG123 MAX SIG123 OR2 DIFF MAX SIG2 H ₁ MAX SIG2 SUM SIG3
25	OR2 AND3DELAY OR3 H ₃ MAX SIG2 H ₂ SUM SIG123 H ₂ DIFF MAX SIG2 MAX SIG123 AND3DELAY OR3 H ₂ SUM SIG2 SUM SIG3 H ₂ DIFF MAX SIG2 MAX SIG123
40	OR2 OR3DELAY AND3 H ₁ MAX SIG2 H ₁ MAX SIG123 H ₂ DIFF SUM SIG2 SUM SIG123 AND3DELAY AND3 H ₃ SUM SIG3 H ₁ SUM SIG2 H ₂ DIFF SUM SIG2 SUM SIG3
50	OR2 OR3DELAY AND3 H ₁ MAX SIG2 H ₁ MAX SIG123 H ₂ DIFF SUM SIG2 SUM SIG123 OR3DELAY AND3 H ₁ MAX SIG3 H ₁ MAX SIG123 H ₂ DIFF SUM SIG3 SUM SIG123
76	OR2 OR3DELAY AND3 H ₁ MAX SIG123 H ₃ SUM SIG2 H ₂ DIFF SUM SIG2 SUM SIG123 OR3DELAY AND3 H ₁ MAX SIG123 H ₃ SUM SIG3 H ₂ DIFF SUM SIG3 SUM SIG123

Table 3: Evolution of the DL given in (21).

Generation	Best Chromosome found in the Population for the Indicated Generation
1	OR2 SUM SIG2 AND3DELAY DIFF SUM SIG2 SUM SIG123
8	OR2 AND3DELAY DIFF SUM SIG3 SUM SIG123 AND3DELAY H ₂ DIFF MAX SIG2 MAX SIG123
16	OR2 AND3DELAY OR3 H ₂ SUM SIG2 SUM SIG3 H ₂ DIFF MAX SIG2 MAX SIG123 OR3DELAY H ₂ OR3 H ₂ SUM SIG2 SUM SIG3 H ₂ DIFF MAX SIG2 MAX SIG123
30	OR2 OR3DELAY AND3 H ₂ MAX SIG123 H ₃ MAX SIG2 H ₂ DIFF MAX SIG2 MAX SIG123 AND3DELAY AND3 H ₃ SUM SIG2 H ₁ SUM SIG123 H ₂ DIFF SUM SIG2 SUM SIG3
46	OR2 OR3DELAY AND3 H ₁ SUM SIG123 H ₃ MAX SIG2 H ₂ DIFF MAX SIG2 MAX SIG123 OR3DELAY AND3 H ₁ SUM SIG123 H ₃ MAX SIG3 H ₂ DIFF MAX SIG3 MAX SIG123

measured output of the digital logic is rarely sufficient to uniquely reverse engineer the design.

Experimental observation and theoretical analysis of the effects of uncertainty show that even when there is a significant reduction in the quality of input-output measurement information: the DL map evolved by the GP will still carry enough information for the design of signals with specific properties. The creation of these signals is considered of greater importance than having the exact DL design for the SD. The signals frequently relate to the determination of control rules for platform or multiplatform automation.

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