AN ENGINEERING CHANGE METHODOLOGY USING SIMULATION RELATIONS

by


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An Engineering Change Methodology using Simulation Relations

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Abstract

In this paper, we address the problem of Engineering Change in a non-deterministic finite state machine framework. We are given a deterministic implementation FSM, and a non-deterministic specification FSM, such that the implementation does not meet the specification. The problem consists of controlling the implementation FSM in such a way that for all possible sequences of external inputs, the generated outputs are allowed in the specification.

We propose a new formalism for the Engineering Change problem which is applicable to non-deterministic specifications. We use the notion of Simulation Relations from the theory of concurrent systems, to develop this new formalism. Our method is cast in the form of a simulation of the implementation by the specification. We prove the necessary and sufficient condition for the existence of a solution to the problem. We also provide an algorithm to obtain all possible solutions under this setting. We have implemented this algorithm, using implicit state enumeration and Reduced Ordered Binary Decision Diagrams (ROBDDs).

An important feature of our method is that the algorithm gives us a solution which is correct by construction, and accordingly we do not need to perform a separate verification step in the design.
1 Introduction

We address the problem of Engineering Change (henceforth EC) [5] in a non-deterministic Finite State Machine (henceforth FSM) setting. We are given a specification, described as a FSM. Further, we are given an implementation, also a FSM, with a different set of inputs. The goal is to create a Controller FSM, which, when composed with the implementation, generates the same output sequence (for a given input sequence) as the specification. In other words, we desire that the composed machine has the same output language as the specification.

In integrated circuit design practice, one often encounters a situation where it is found that the circuit implemented on silicon does not perform according to the specification. The designer would like to alter the functionality of a single die, on an experimental basis, and see if the altered circuit performs according to the specification. If it does, the change is incorporated in the next mask revision. This capability significantly reduces the cost of EC, by reducing the number of EC iterations, and also reduces turnaround time between mask revisions.

In current day technology, this experimental change in the functionality of a single die is done by a Focussed Ion Beam (FIB) apparatus. The operator has the capability to view a section of the die under an electron microscope, identify the wire on the die that is to be cut, perform the cut, and deposit new wires on the die. These wires contact both the endpoints of the cut wire, and run over the passivation layer to an uncommitted gate. The wire is cut by bombarding the passivation layer and the wire with a focussed beam of ions. In the pit that is thus formed, new wires can be deposited and run to an uncommitted gate. There are regions of the layout that contain a variety of different uncommitted gates. In this way, the new gate is introduced in the circuit.
The FIB operations are illustrated in figure 1. In this figure, it was determined that an inversion was required between signals $a$ and $b$. The wire between $a$ and $b$ is cut by a FIB, and new wires are deposited and run to a spare inverter, shown on the right side of the figure.

In practice, this process is mainly used to alter combinational circuit functionality. The changes are usually performed in an ad-hoc manual fashion. Recent research [6] addresses this problem, and an algorithm is provided which determines whether a given function is implementable using an array of gates. This array
could be the gates of the implementation, along with the spare gates. For sequential circuits, however, we need to come up with a new FSM, such that the combined behavior of the old FSM and the new one meets the specification. This is too difficult to be done manually; it is for this reason that sequential circuits are not effectively handled in the engineering change scenario. Our paper provides an automated approach to engineering change in a sequential, non-deterministic setting.

In the engineering change scenario outlined above, it is important to keep the number of wires to be cut and re-routed to a minimum. The cost of a FIB cut is greater than that of opening up the passivation layer to form a contact. For this reason, the FSM configuration in figure 6 is a preferred one, since the outputs of the implementation are unaltered in this formalism. Accordingly, in our discussion, we focus on this configuration alone.

We prove the necessary and sufficient condition for the existence of a solution to the EC problem. Further, we present an algorithm to construct a maximal solution called the "controller", and prove that it contains all the feasible solutions. The advantage of our approach is that the maximal controller is verified by construction, so a separate design phase is not required.

Our problem formulation makes for easier understanding of the proofs and, we believe, is a good launching point for future research in the field.

2 Previous Work

Previous work in the EC for FSMs has been mainly in two directions. We briefly discuss these, and indicate how our approach is different.

The area of Model Matching within the area of Discrete Event Dynamical Systems (DEDS) has recently received attention in the Control Systems Engineering area. Here, the specification (called a Model) and the implementation (called a Plant) are given. A Controller FSM is to be synthesized, such that the composed behavior of the controller and the plant “matches” the behavior of the model in some specialized sense.

Recent developments in this area include the Strong Model Matching [4] (henceforth SMM) and
Generalized Strong Model Matching [3] (henceforth GSMM) works. In these works, the implementation and the specification are assumed deterministic, and the desired goal is output language equality. In SMM, the controller is free to alter the inputs from the environment to "trick" the specification into behaving appropriately. But, unlike GSMM, the controller cannot alter the outputs of the specification.

We propose a more general approach than SMM by relaxing the requirement of determinism on the specification. In addition, our approach can also handle a restricted notion of non-determinism (known as pseudo non—determinism), in the implementation FSM.

In another work, Watanabe and Brayton [13] addressed the problem of finding the "maximum set of permissible behaviors" for a component FSM in a system of interacting FSMs. They derive a non-deterministic FSM called the $E$—machine which "captures" this maximal set of permissible behaviors.

We utilize the notion of a simulation relation [8] from concurrency theory to develop a simpler and more elegant treatment of the EC problem, and find a "correcting" FSM which minimally restricts the behavior of the implementation when composed with it. In this way, we derive an alternate characterization of the "maximal set of permissible behaviors"; we show that there exists a simulation relation from any admissible FSM into the non-deterministic FSM representing the set of all permissible behaviors.

3 Preliminaries and Definitions

We represent a set by an upper case English letter; an element of a set is represented by a lower case English letter.

**Definition 1** A Finite State Machine (FSM) is a 5-tuple $M(I, O, S, R, r)$ where $I$ is the input alphabet, $O$ the output alphabet, $S$ a finite set of states, $R \subseteq S \times S \times I \times O$ the output and transition relation, and $r$ the initial state. In some cases, the relation $R$ is alternately represented as a output relation $\gamma \subseteq S \times I \times O$ and a state transition relation $\lambda \subseteq S \times S \times I$.

If the output and the next state are uniquely defined for a given input and present state, then the FSM is called a Deterministic Finite State Machine (DFSM), else it is called a Non-deterministic Finite State Machine (NDFSM). Examples are shown in figures 2 and 3.
If the next state is uniquely defined for a given present state, input and output, then the FSM is called **Pseudo Non-deterministic**. An example is shown in figure 4.

If the relations $\gamma$ and $\lambda$ are total, then $M$ is said to be **completely specified**, else it is **incompletely specified**. If an input $i \in I$ is not applicable at state $s$, then $\lambda(s, i)$ is empty. In such a situation, we assign $\lambda(s, i) = \theta$, where $\theta$ is the **dead state**.

**Definition 2** *There exists a Simulation Relation (abbreviated SR) from a FSM $M_1$ to a FSM $M_2$ if there exists a relation $\psi \subseteq S_1 \times S_2$ such that*

1. $(r_1, r_2) \in \psi$
2. $(s_1, s_2) \in \psi \Rightarrow \forall i, \forall o, \forall s_1'(i(R_1(s_1, s_1', i, o) = 1) \Rightarrow \exists s_2'((R_2(s_2, s_2', i, o) = 1) \land (\psi(s_1', s_2') = 1)))$

We denote the above condition $M_1 \leq M_2$. We alternately denote $R_1(s_1, s_1', i, o) = 1$ by $s_1 \xrightarrow{i/o} s_1'$. This means that there is a transition from state $s_1$ to state $s_1'$ under an input $i$ which produces output $o$.

**Definition 3** Given FSMs $M_1(U, Y, S_1, R_1, r_1)$ and $M_2((V, Y), U, S_2, R_2, r_2)$, the composition $\hat{M}(V, Y, \hat{S}, \hat{R}, \hat{r}) = M_1 \circ M_2$ satisfies the following properties:

1. $\hat{S} = S_1 \times S_2$
2. $\hat{r} = (r_1, r_2)$
3. $\hat{R}(\hat{s}, \hat{s}', v, y) = 1$ iff $\exists u[[R_1(s_1, s_1', u, y) = 1] \land [R_2(s_2, s_2', (v, y), u)] = 1]$

The composed machine $\hat{S}$ makes a transition $\hat{s} \xrightarrow{u/y} \hat{s}'$ iff $\exists u[(s_1 \xrightarrow{u/y} s_1')$ in $M_1 \land s_2 \xrightarrow{(v,y)/u} s_2']$

### 4 Problem Statement

The EC problem is stated formally as follows:

**Problem Statement 4.1** Given FSMs $M_1(U, Y, S_1, R_1, r_1)$ and $M(V, Y, S, R, r)$, the specification matching problem of EC consists of finding a FSM $M_2((V, Y), U, S_2, R_2, r_2)$ such that $M_1 \circ M_2 \preceq M$.

For our purpose, we assume that $M_1$ is deterministic, and $M_2$ is non-deterministic. The configuration of $M_1$ and $M_2$ is as in [4], and is shown in figure 6. We borrow the terminology of [4] and call $M_1$ as plant, $M_2$ as the controller and $M$ as the model.
5 Our Approach

In this paper, we assume that $M$ is non-deterministic, and that $M_1$ is deterministic. The assumption that $M_1$ is deterministic is reasonable, since in most real problems, the implementation is a deterministic one. However, $M$ can be non-deterministic in real problems. This corresponds to the designer of the system providing multiple acceptable specification behaviors. The designer would like the implementation to match any acceptable specification behavior.

We would like to do output language equality if possible, otherwise we perform output language containment. In a sense, we are trying to match as much of the specification’s behavior as possible.

Our formulation of the problem is a Simulation Relation from the implementation into the specification. We define a relation $H_{max}$, which extracts the "maximal" behavior of the specification that can be matched by the implementation. Also, it "removes" behaviors of the implementation that are not contained in the specification.

Definition 4 $(s_1, s) \in H_{max} \iff \forall v \exists u \forall y \exists s'_1 [(s_1 \xrightarrow{u/y} s'_1) \Rightarrow \exists s' [(s \xrightarrow{v/y} s') \land (s'_1, s') \in H_{max}]]$

Intuitively, $s_1$ can simulate $s$ if and only if for all $v$ that the environment can produce, the controller can give the plant an input $u$ such that both $M_1$ and $M$ produce the same output and the next state of $M_1$ can simulate the next state of $M$.

Intuitively, the above definition is like a simulation relation with different labels on the transitions. The above definition suggests a symbolic greatest fixed point implementation [7] of $H_{max}$.

In the following theorem we provide the necessary and sufficient condition for the solution of the problem to exist. We prove that the problem of EC is solvable if and only if the initial states $r_1$ and $r$ of $M_1$ and $M$
respectively are related in $H_{\text{max}}$.

**Theorem 5.1** The specification matching problem has a solution iff $(r_1, r) \in H_{\text{max}}$

**Proof:** Only if part: Given that $(r_1, r) \in H_{\text{max}}$. We have to show that for any arbitrary $k$ and for all sequences $v_0v_1...v_k$ there exists a sequence $u_0u_1...u_k$ such that the outputs $y_0y_1...y_k$ produced by both implementation and the specification are the same. We prove this by induction on the length of the sequence.

- **length = 1:** By the definition of $H_{\text{max}}$, $\forall v_0 \exists u_0$ s.t. if $r_1 \xrightarrow{u_0/y_0} s_1$ in $M_1$, then $r \xrightarrow{u_0/y_0} s$ in $M$, and $(s_1, s) \in H_{\text{max}}$

- **Induction Hypothesis:** Assume, for any sequence $v_0v_1v_2...v_k \exists u_0u_1...u_k$ s.t. if $r_1 \xrightarrow{u_0/y_0} s_1 \xrightarrow{u_1/y_1} s_1^1 \xrightarrow{u_2/y_2} \ldots \xrightarrow{u_k/y_k} s^k$ and $(s^k_1, s^k) \in H_{\text{max}}$ in $M$

- **length = k+1:** By definition of $H_{\text{max}}$, for an arbitrary $v_{k+1} \exists u_{k+1}$ s.t. if $s^k_1 \xrightarrow{u_{k+1}/y_{k+1}} s^k_{k+1}$, then $s^k \xrightarrow{u_{k+1}/y_{k+1}} s^k_{k+1}$, and $(s^k_{k+1}, s^k_{k+1}) \in H_{\text{max}}$

Therefore, the claim follows by induction on the length of the sequence.

If part: Since the specification matching problem is solvable, we know that $\exists M_2$ such that $M_1 \circ M_2 \preceq M$.

We need to show that $(r_1, r) \in H_{\text{max}}$.

From the definition of $\text{SR}$, we know that there exists a relation $\varphi$ relating state $(r_1, r_2)$ of $M_1 \circ M_2$ with state $r$ of $M$, such that

- $((r_1, r_2), r) \in \varphi$

- $((s_1, s_2), s) \in \varphi \Rightarrow \forall u \forall v$ if $[(s_1, s_2) \xrightarrow{u/y} (s'_1, s'_2)]$ then $\exists s'$ s.t. $[s \xrightarrow{u/y} s']$.

By definition of composition, if $[(s_1, s_2) \xrightarrow{u/y} (s'_1, s'_2)]$ in $M_1 \circ M_2$ then $\exists u$ such that $s_1 \xrightarrow{u/y} s_1'$ in $M_1$. Now we define a new relation $\phi$ relating these states of $M$ and $M_1$ such that

- $(r, r_1) \in \phi$

- $(s, s_1) \in \phi \Rightarrow (s', s'_1) \in \phi$

Hence for any infinite sequence $v_0v_1v_2..., \exists u_0u_1u_2...$ s.t. if $r_1 \xrightarrow{u_0/y_0} s_1 \xrightarrow{u_1/y_1} s_1^1 \xrightarrow{u_2/y_2} \ldots \text{ in } M_1$, then $r \xrightarrow{u_0/y_0} s \xrightarrow{u_1/y_1} s^1 \xrightarrow{u_2/y_2} \ldots \text{ in } M$.,
Therefore, by definition of \( H_{\text{max}} \), we have \((r_1, r) \in H_{\text{max}}\).

5.1 Deriving the Maximal Controller

In this section we characterize all the possible solutions to the engineering change problem by an NDFSM \( M_c \) called the controller. This controller is maximal in the sense that any FSM which is a solution to the problem will have a simulation into \( M_c \) and any FSM which has a simulation into \( M_c \) will be a solution of the problem. The maximal controller \( M_c((V, Y), U, S_c, R_c, r_c) \) is constructed as follows:

- \( S_c \subseteq S_1 \times S = \{(s_1, s) \mid (s_1, s) \in H_{\text{max}}\} \)

- \( r_c = (r_1, r) \)

- \( R_c((s_1, s), (s'_1, s'), (v, y), u) = 1 \iff \left[(R_1(s_1, s'_1, u, y) = 1) \land (R(s, s', v, y) = 1)\right] \)

The states of the controller are those in the cross product of the set of states of the plant and the specification which are present in \( H_{\text{max}} \). There is a transition in the controller from \((s_1, s)\) to \((s'_1, s')\) on \((v, y)\) with an output \(u\) if and only if there is a transition from \(s_1\) to \(s'_1\) on \(u\) in \( M_1 \) and a transition from \(s\) to \(s'\) on \(v\) in \( M \), both producing the same output \(y\).

In the following theorems, we claim the maximality of \( M_c \) by

- showing that \( M_c \) composed with \( M \) has a simulation into \( M \),

- showing that any solution of the problem has a simulation into \( M_c \), and

- any FSM that has a simulation into \( M_c \) is a solution.

**Theorem 5.2** Let \( M_1 \circ M_c = \hat{M}(V, Y, \hat{S}, \hat{R}, \hat{r}). \) Then \( \hat{M} \preceq M \).

**Proof:** By the definition of composition, for \( \hat{s} = (s_1, (\hat{s}_1, s)) \) and \( \hat{s}' = (s'_1, (\hat{s}'_1, s')) \), if \( [\hat{s}, \overset{v/y}{\rightarrow} \hat{s}'] \), then

\( \exists u \) such that \([s_1 \overset{u/y}{\rightarrow} s'_1]\) in \( M_1 \) and \([[(\hat{s}_1, s) \overset{(v/y)\uparrow u}{\rightarrow} (\hat{s}'_1, s')]\) in \( M_c \).
Similarly, if \((s_1, s)^{(v,y)} \rightarrow^u (s_1', s')\) in \(M_c\) then, by definition of \(R_c\)
\[[s_1 \stackrel{u}{\rightarrow} s_1'] \text{ in } M_1 \text{ and } [s \stackrel{v}{\rightarrow} s'] \text{ in } M.\]

Now, we define a relation \(\phi\) such that for all \(\hat{s} = (s_1, (\hat{s}, s)), (\hat{s}, s) \in \phi.\)

Clearly,

- \((\hat{r}, r) \in \phi, \text{ since } \hat{r} = (r_1, (r_1, r)), \text{ and}\)

- \((\hat{s}, s) \in \phi \Rightarrow [\forall v \forall y \forall (s' = (s_1', (s_1', s'))) \hat{s} \stackrel{v/y}{\rightarrow} s'] \text{ in } M_c \Rightarrow \exists s' [s \stackrel{v/y}{\rightarrow} s'] \text{ in } M \text{ and } (s', s') \in \phi] \]

Accordingly, there is a simulation from \(\hat{M}\) to \(M.\)

\[\text{Theorem 5.3 } M_2 \preceq M_c \implies M_1 \circ M_2 \preceq M.\]

Proof: Only if part: Since \(M_2 \preceq M_c\), and \(M_1 \circ M_c \preceq M\) (by theorem 5.2), it follows that \(M_1 \circ M_2 \preceq M.\)

If part: Given that \(M_1 \circ M_2 \preceq M\), there exists a relation \(\varphi\) such that

- \(((r_1, r_2), r) \in \varphi\)

- \(((s_1, s_2), s) \in \varphi \Rightarrow [\forall v \forall y \forall (s' = (s_1', (s_1', s'))) \text{ if } [(s_1, s_2) \stackrel{v/y}{\rightarrow} (s_1', s_2')] \text{ in } M_1 \circ M_2 \Rightarrow \exists s' [s \stackrel{v/y}{\rightarrow} s'] \text{ in } M \text{ and } ((s_1', s_2'), s') \in \varphi]\]

Also, \([(s_1, s_2) \stackrel{v/y}{\rightarrow} (s_1', s_2')] \text{ in } M_1 \circ M_2\) implies, from the definition of composition,

\[\exists u [s_2 \stackrel{(v,y)}{\rightarrow} u s_2'] \text{ in } M_2 \text{ and } [s_1 \stackrel{u}{\rightarrow} u s_1']\]

Since \((r_1, r) \in H_{max}\) and \(M_1\) is deterministic, by definition of \(H_{max}\), \(s_c = (s_1, s) \in H_{max}\) and \(s_c' = (s_1', s) \in H_{max}\).

Also, since \([s_1 \stackrel{u}{\rightarrow} u s_1'] \text{ in } M_1\) and \([s \stackrel{v/y}{\rightarrow} s'] \text{ in } M\), then by definition of \(R_c\), \([(s_1, s) \stackrel{(v,y)}{\rightarrow} (s_1', s')]\).

So, define a relation \(\tau\) such that

- \((r_2, r_c) \in \tau\)

- \((s_2, s_c) \in \tau \Rightarrow (s_2', s_c') \in \tau\) where \(s_2', s_c'\) denote the same states that are referred before.
6 Implementation and Results

The approach presented in the section 5 has been implemented (about 1500 lines of C) in the SIS [10] environment. The implementation assumes a fully specified NDFSM description for the specification and an incompletely specified DFSM description for the implementation.

About 1500 lines of C code has been written. Starting with an FSM description in the kiss format, the program builds the transition relation [12], performs the fixed point computation for $H_{max}$ and checks that $(r_1, r) \in H_{max}$, i.e. the problem is solvable. If so, then the transition relation for $M_c$ is built. All computations are done implicitly using ROBDDs [2] [1].

We present the results of our experiments below. In Table 1, 'Controllable' represents that the implementation can be controlled to match the specification's behavior for all inputs and 'Not Controllable' represents that the implementation cannot match the specification's behavior. Figure 7 shows two example machines from Table 1.

7 Conclusions

We have addressed the problem of EC of FSM's in a non-deterministic setting. This problem consists of synthesizing a finite state controller for a implementation such that the closed loop behavior of the controller composed with the implementation can be simulated in the specification. Both implementation and specification are represented as FSM's. Our contributions are as follows:

- A new formalism for the EC problem was proposed. Our formalism handles both deterministic and non-deterministic specifications.
- The problem is cast as a simulation of the implementation into the specification.
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Table 1: Implementation Results

Figure 7: Examples oex4 and oex5 from table of results
• A necessary and sufficient condition for the solvability of the problem is given.

• A procedure to construct the 'maximal' controller $M_c$ was presented.

• We prove that any FSM which has a simulation into $M_c$ is a solution to the problem and all the solutions to the problem are contained in $M_c$.

• It can be shown easily that the strong model matching problem [4] is a special case of this formulation.

• The entire code has been implemented in SIS. All computations are done implicitly using BDDs for greater efficiency.

8 Future Work

There are some definite directions that remain to be explored as a sequel to this work. We would like to use our formulation to address the problem of stochastic languages [9]. Currently, in our work, we do not consider the infinitary properties of the FSMs. This work has received some interesting treatment in [11], and warrants study in our framework.

We see many opportunities to improve the code that has been written so far. For example, we could explore the use of partitioned transition relations. Various heuristics for ROBDD variable ordering are available; we need to find out the most suitable one in the context of specification matching. Other techniques to improve efficiency, like early quantification of variables and the use of different encoding techniques for FSMs have to be fully investigated. The code needs to be interfaced with an FSM determinization program to select the minimum state controller contained in $M_c$.

References


