Formal Verification for Node-Based Visual Scripts
Using Symbolic Model Checking

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Abstract—Visual script languages with a node-based interface have commonly been used in the video game industry. We examined the bug database obtained in the development of FINAL FANTASY XV (FFXV), and noticed that several types of bugs were caused by simple mis-descriptions of visual scripts and could therefore be mechanically detected.

We propose a method for the automatic verification of visual scripts in order to improve productivity of video game development. Our method can automatically detect those bugs by using symbolic model checking. We show a translation algorithm which can automatically convert a visual script to an input model for NuSMV that is an implementation of symbolic model checking.

For a preliminary evaluation, we applied our method to visual scripts used in the production for FFXV. The evaluation results demonstrate that our method can detect bugs of scripts and works well in a reasonable time.

Index Terms—Formal methods, Symbolic model checking, Visual script, Game development

I. INTRODUCTION

A. Background

In the recent video game industry, game designers write game logic using script languages. Although most of game designers are not familiar with writing programs, the use of visual script languages allow such designers to describe game logic, and thus can improve the productivity of game development. In particular, visual script languages with a node-based interface are widely used in game development.

However, it is hard to maintain game logic written in visual script languages because such scripts can quickly become large and complicated during the development process, and thus become hard to be verified or modified, and very prone to human error.

We examined the bug database obtained in the development of FINAL FANTASY XV (FFXV) [1], and noticed that several types of bugs were caused indeed by simple mis-descriptions of visual scripts. A system that can automatically detect such mis-descriptions would had been a great help to our production.

Most visual script implementations could be treated as a kind of state machine [2]. While model checking is a well-researched technique to automatically verify finite state machines [3] [4]. We thus propose in this paper a method for automatic verification of visual script notations with symbolic model checking [5] for efficient game production. Our main contributions are the following. (1) To apply symbolic model checking to verify visual scripts, we provide a translation algorithm from a visual script description to an input model for NuSMV [6], that is an implementation of symbolic model checking. (2) We show a preliminary evaluation of our method by applying it to visual scripts which are produced in the development of FFXV, and demonstrate that most of the verification tasks are completed in a realistic amount of time.

This paper is an extended version of our work published at ICFEM 2019 [7]. The rest of this paper is organized as follows. Section II explains the proposed method. Section III provides the translation algorithm from a visual script to an input model which can be accepted to NuSMV. We additionally provide the method for optimizing the SMV program in order to reduce the state space in Section IV. We show the results of our preliminary evaluation in Section V and conclude our work in Section VI.

B. Model Checking

Model checking is an automatic technique for verifying correctness properties of a finite-state system [8]. The verification procedure is performed by an exhaustive search over the state space. Since the size of the state space exponentially increases with the number of system components, it is difficult to apply model checking to large-scale systems. Symbolic model checking can efficiently handle large-scale systems by replacing explicit state representation with boolean formula.

NuSMV [6] is one of the most successful implementations of symbolic model checking. The model verified by NuSMV is written by a specific input language (called SMV language). The properties to be checked is expressed by temporal logic LTL (Linear Temporal Logic) [9] and CTL (Computational Tree Logic) [10].

MODULE main
VAR
sw : {on, off};
ASSIGN
init(sw) := {on, off};
next(sw) := case
sw = on : off;
TRUE : sw;
esac;
CTLSPEC AG (AF sw = on)

Fig. 1. An example model described in SMV language
Fig. 1 is an example of an input model to NuSMV. The input model described by SMV language is composed of variable declaration part (described by VAR) and transition relation definition part (described by ASSIGN). The property is expressed as a LTL formula (described by LTLSPEC) or a CTL formula (described by CTLSPEC).

This example has one variable \( sw \) which may have one of the two values \( on \) and \( off \). In its initial state, either \( on \) or \( off \) is assigned to \( sw \) non-deterministically. In the case that \( sw \) is \( on \), \( sw \) becomes \( off \) in the next state, or \( sw \) does not change its value. Thus the sequence of the value of \( sw \) can be either \( on, off, off \ldots \) (when the initial value is \( on \)) or \( off, off \ldots \) (when the initial value is \( off \)). The CTL formula in this example has two CTL operators \( AG \) and \( AF \). \( AG \) represents “in Any path” and “Globally,” and \( AF \) represents “in Any path” and “in the Future.” This formula expresses the following property: the system always satisfies \( sw = on \). The result and the counterexample generated by NuSMV. The counterexample shows the path where \( sw \) continues to be \( off \).

1. -- specification AG (AF sw = on) is false
2. -- as demonstrated by the following
3. execution sequence
4. Trace Description: CTL Counterexample
5. Trace Type: Counterexample
6. -> State: 1.1 <-
7. sw = on
8. -- Loop starts here
9. -> State: 1.2 <-
10. sw = off
11. -> State: 1.3 <-

Fig. 2. A counterexample generated by NuSMV

C. Related Work

Video games essentially have a large number of combinations of internal states and external stimuli. This makes it difficult to detect problems which come out under specific conditions by testing. Model checking has been applied to video game development since it can solve such problems by exhaustive verification. Moreno-Ger et al. [11] proposed a method for verifying game scripts created in (e-Adventure) platform using NuSMV. Radomski et al. [12] showed a framework in which video game logics are modeled by State Chart XML (SCXML) formalism and their properties can be checked by the SPIN model checker. Rezin et al. [13] developed a method to model a multi-player game design as a Kripke structure and to verify it by NuSMV. These studies show that applying model checking to video game development is very promising and application to game logic described by node-based visual scripts is also expected.

There have been a number of studies that have applied model checking to verification of node-based state transition system designs. Statecharts and its variants, such as UML state machine [14] and RSML (Requirements State Machine Language) [15], are one of the most popular notations for describing state transition systems in a node-based manner. Chan et al. [16] provided a translation from RSML notation to a model described by SMV language. This translation procedure encodes components of the inputted RSML by SMV variables and expresses changes of the components as transition relation. Zhao et al. [17] studied representation of Statecharts step-semantics as a Kripke structure, which is a graph-based state transition representation, and carried out verification using SMV model-checker. Jussila et al. [16] presented a representation of a subset of UML state machines as Promela which is an input language of SPIN model-checker.

In the semantics of Statecharts and its variants, their nodes represent states and only simple actions (enter/exit or do action in the case of UML state machine) can be assigned to each node. While in the visual script notations that we focus, each node expresses some game logic computation which can be performed individually and can have a particular semantics. Thus it is difficult to directly apply the existing procedures to the verification of such a visual script notation. In this paper, we propose a method to translate from visual scripts to models by SMV language.

II. APPROACH

A. Motivating Example

Many game development environments have their own visual scripting system such as Blueprint in Unreal Engine 4 [17], Lumberyard ScriptCanvas [18], and the VFX development tool for FFXV [19]. Although there are slight differences among each visual scripting systems, their syntax and semantics are basically the same. In this paper, readers can assume Blueprint [17] as the visual scripting system since its syntax and semantics are very similar to our in-house visual scripting system.

In the development with node-based visual script languages, logic is described as a node graph which is composed of nodes and edges. Nodes express values, variables, arithmetic operators, or control statements which correspond to if/while-statements in text-based script languages. Since the purpose of visual scripts is to control game components such as sound, visual effect, and so on, many nodes express invocations of APIs for those components. For example, “Play SE” node notifies sound component of the game system to start playing sound effect, “Fade Out” node notifies screen effect component to start fade-out effect [1]. Edges connect nodes through input and output ports, and express data and control flows.

Fig. 3 shows an example of visual script. For simplicity, we omitted data flow edges such as the condition value inputted to If node. This is because our method does not address the detection of bugs caused by an illegal data flow.

This example has the following behavior:

1."Fade out" is a gradual transition from the game screen to blank image, used in movies, games, etc.
• The Set Event Mode node changes the value of the global flag variable event mode. When it receives the input signal through the Enable or Disable port, the event mode flag becomes true or false respectively. This example includes two Set Event Mode nodes, and both of them modify the same variable instance because the event mode is a global variable referred from the whole game system.

• When the Movie Clip node receives an input signal through the Start port, it starts playing the movie clip, and sends output signal through the Finished port when the clip finishes. If the movie clip is skipped by a player, it sends output signal through the Skipped port instead of the Finished port.

• The If node performs conditional branching. Depending on the condition value, it outputs signal through the True or False port. Its condition value is inputted through data flow port (As stated above, we omit such ports).

• The value of event mode must be true while the movie clip is playing in order to change the game state appropriately. (For instance, the gamepad is disabled during the movie.) On the other hand, it must be false when the movie clip is not playing.

Note that the Movie Clip node has internal states and sends Finished and Skipped signal depending on its internal state. Since its output signals are activated independently of the original control flow through the input port, there can be multiple activated nodes and multiple activated control signals simultaneously in the graph. This is one of the major differences between visual script languages and Statecharts, and the reason why prior researches cannot be applied directly to the verification of visual scripting languages.

This example contains a bug that actually occurred frequently during the development of FFXV. As you can see, the False port of the If node is not connected to any port. Therefore, in the case that the If node branches to False after the Movie Clip node outputs Skipped signal, the event mode flag will not be changed and will remain true. As a result, the event mode flag will remain true even though the movie clip has finished playing, resulting in incorrect behavior.

There were a wide variety of similar bugs during the development of FFXV, e.g., “BGM is not changed correctly in some cases,” “Enemy characters never respawn in a specific condition,” and so on. Although these bugs are caused by trivial mis-descriptions such as missing one node or edge, it is tough to find those bugs by visual inspection. This is due to the fact that many game logic scripts are described by game designers who are not familiar with programming, and thus the script becomes large and complicated. Our goal is to detect those large amounts of trivial but hard-to-find bugs automatically and exhaustively. Since our products already have a lot of massive scripts, we should cover not only newly written scripts but also those existing scripts.

B. Overview

Fig. 4 shows the system overview of the visual script verification environment with NuSMV. This environment carries out verification by converting a visual script into an SMV model. First, the system generates a converter instance from specifications to be checked and the corresponding node semantics. Then the visual script is converted into an SMV model by using the converter instance. NuSMV can verify whether the inputted visual script satisfies the specifications or not. When the specifications are not satisfied, NuSMV outputs counterexamples.

In our system, specifications and node semantics need to be written manually. However, once they are given, the verification process can be fully automated. Specifications for detecting typical bugs can be represented by simple formulas in temporal logic. Also, since the behavior of many nodes is common, many nodes can be converted to SMV models by writing a single node semantics.

1) Specification: In our visual script verification environment, specifications are expressed by propositional temporal formulas. Since NuSMV supports temporal formulas written in CTL and LTL, the specification must be written in those logics in our system as well.

For example, in order to detect the bugs explained in Fig. 3-A, we provide the specification expressed as the following CTL formula:

$$AG(event\ mode = true \rightarrow AF(event\ mode = false))$$

This formula represents that it is always satisfied that event mode flag must eventually become false if the flag is true.

2) Node Semantics: Each node has input or output ports, and internal states (if the node has state transition). It also can change the values of global variables. The output signal of the node depends on its input signal and its internal state. The internal state of the node changes according to its input signals and its current state. Thus the transition relation of the
value of the output signal and the internal state of the node is generally expressed the following formula:

\[ out' \equiv f_{\text{out}}(in, state), \]
\[ state' \equiv f_{\text{state}}(in, state). \]

in, out and state denote the value of the input signal, output signal and internal state, respectively. The primed symbol denotes the value after the transition.

Also, the transition relation of the values of global variable changed by the node is similarly expressed the following formula:

\[ var' \equiv f_{\text{var}}(in, state, var). \]

var denotes the values of global variable. For example, the Set Event Mode node has the following relation:

\[ out' \equiv \text{if} (in = \text{Enable} | in = \text{Disable}) \text{ then Out else none,} \]
\[ \text{event mode}' \equiv \text{if} (in = \text{Enable}) \text{ then true else if} (in = \text{Disable}) \text{ then false else event mode.} \]

We refer the transition relation of the elements involved in the node as node semantics. Initial values of elements are also defined in node semantics.

In our system, node semantics are given as templates for an SMV program that define the transition relation. Fig. 5 shows the example of node semantics for the Set Event Mode node. Note that this definition only depends on the elements involved in the node. We thus can describe node semantics independent from graph structure.

Our translation algorithm generates an SMV program by appropriately assigning variables to the node semantics of all nodes. For example, since Fig. 3 has two Set Event Mode nodes, our algorithm applies the node semantics to these nodes and assigns different variables to them.

1) Variables: We prepare four types of SMV variables to describe the behavior of a visual script.

- **Input and output variables** represent activated ports of each node. Since only one input and output port of the nodes can be activated at the same time, we declare one input and output variable for each node. For example, the input and output variable for the leftmost Set Event Mode node is defined as SetEventMode2In and SetEventMode2Out, respectively (see Fig. 6(1)). The domain of an input and output variable is defined as the names of its input and output port and special value none which denotes that no port is activated. Since Set Event Mode node has two input ports Enable and Disable, the input variable SetEventMode2In has the domain {none, Enable, Disable}. The initial value of the input and output variable is set to none (see Fig. 6(5) and (8)).

- **Script variables** represent global variables of the visual script and information of external components that the visual script interacts with. Specifications are often expressed as correct behaviors of those variables. For example, the script variable for the global variable event mode, which is a flag variable of the external game system that the visual scripts interact with, is defined as EventMode (see Fig. 6(3)).

- **State variables** represent the internal state of each node which has state transition semantics. For example, the state variable for Movie Clip node is defined as MovieClip3State (see Fig. 6(2)). The domain of a state variable is defined as a set of its internal states. Since Movie Clip node has four internal states, the state variable MovieClip3State has the domain {Stopped, Playing, Finished, Skipped}.

2) Control Flows: Control flows in a visual script are represented as propagation of signals through the edges between the nodes. When an output port is activated, then the input port connected through the edge to the output port is activated. Therefore, we can describe such propagation of signal in an SMV model as value assignments for input variables according to the values of output variables.

For example, the input port Enable of the leftmost Set Event Mode node is connected to the output port Out of Script Start node. Thus the value of the input variable SetEventMode2In changes to Enable when the output variable ScriptStart1Out has the value Out (see Fig. 6(7)).

The signal propagation representing the control flow of a visual script is reproduced as value transitions in an SMV model. For example, the following is one of the control flows of the visual script in Fig. 3.

\[
\text{ScriptStart}: \text{Out} \rightarrow \text{SetEventMode}: \text{Enable} \rightarrow \text{SetEventMode}: \text{Out} \rightarrow \text{MovieClip}: \text{Skipped} \rightarrow \text{If}: \text{In} \rightarrow \text{If}: \text{False}.
\]

C. Translating Example

We first show the overview of the translation using the example visual script shown in Fig. 3. Fig. 6 is an SMV model obtained from the visual script.

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Fig. 5. An example of node semantics

1. @SetEventMode::define::output_variable
2. int(<output_variable>) := none;
3. next(<output_variable>) := case
4. <input_variable> = Enable | <input_variable> = Disable => Out;
5. TRUE := none;
6. esac;
7. @SetEventMode::rule::EventMode
8. <input_variable> = Enable => true;
9. <input_variable> = Disable => false;
Fig. 6. Converted SMV model

This control flow is obtained as value transitions of SMV variables shown in Fig. 7.

3) Nodes: Each node activates its output ports and changes the value of global variables according to the input signals and
SetEventMode4Out and the script variable EventMode. The movie clip is skipped, and the node sends the output signal Skipped.

Thus the node semantics of the Movie Clip node is defined as follows:

\[
\begin{align*}
\text{out}' & \equiv f_{\text{out}}(\text{state}) \\
& = \begin{cases} 
\text{Finished} & \text{if state = Finished} \\
\text{Skipped} & \text{else if state = Skipped} \\
\text{none} & \text{else}
\end{cases},
\end{align*}
\]

\[
\begin{align*}
\text{state}' & \equiv f_{\text{state}}(\text{in, state}) \\
& = \begin{cases} 
\text{Playing} & \text{if in = Start then} \\
\text{Skipped} & \text{else if state = Playing} \\
\{\text{Playing, Finished, Skipped}\} & \text{else}
\end{cases}
\end{align*}
\]

We can describe the behavior of the node as the assignment of values of output variable MovieClip3Out and state variable MovieClip3State as follows:

- The initial state is Stopped (see Fig. 6(11)).
- When receiving the input signal Start, the state changes to Playing (see Fig. 6(12)).
- When the state is Playing, it changes to either Playing, Finished, or Skipped non-deterministically (see Fig. 6(13)). This non-deterministic choice represents the behavior of the game player, who may skip the movie or wait until it is finished playing.
- When the state changes to Finished or Skipped, the node sends the output signal Finished or Skipped respectively (see Fig. 6(10)). Then the state is back to Stopped (see Fig. 6(14)).

### If node
The If node branches True or False according to the condition value. Since we do not consider data flow and external behavior which affects the condition value, we model this branch to decide the output signal non-deterministically. Thus the value True or False is assigned to the output signal of the node non-deterministically (see Fig. 6(16)). NuSMV can check the both branch of True and False exhaustively.

### Script Start node
The Script Start node is an entry point node and sends the output signal once in the initial state. Thus the initial value of the output signal of the node is set to Out and from then on, it will always be none (see Fig. 6(5)).

4) Specification: Specifications are expressed as temporal formulas over script variables. As stated in [II-B], the specification formula that can detect the expected bug is expressed as a CTL formula. In an SMV model, such formula is annotated by CTLSPEC statement (see Fig. 6(18)).

5) Counterexample: As we stated in [II-C], a control flow of a node graph correspond to value transitions of input and output variables. If the property given by CTLSPEC is violated, NuSMV generates a counterexample which indicates the witness of property violation. Since the counterexample can be obtained as the form of the value transitions of SMV variables, we can identify the control flow which causes the violation from the counterexample.

For example, NuSMV can detect the bug and generates a counterexample that shows a value transition shown in Fig. 7.

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### Fig. 7. Value transitions of the example control flow obtained by NuSMV

| State | Transition | Event Mode | Script Start1Out | SetEventMode2In | SetEventMode2Out | MovieClip3State | MovieClip3Out |
|-------|------------|------------|------------------|-----------------|-----------------|----------------|--------------|
| 1.1   | State:     | False      | Out              | none            | none            | none           | none         |
| 1.2   | State:     | 1.4        | none             | Enable          | none            | none           | none         |
| 1.3   | State:     | 1.5        | none             | none            | Out             | none           | none         |
| 1.4   | State:     | 1.6        | none             | Start           | none            | none           | none         |
| 1.5   | State:     | 1.9        | none             | none            | none            | none           | none         |
| 1.6   | State:     | 1.7        | none             | none            | Out             | none           | none         |
| 1.7   | State:     | 1.8        | none             | none            | Stopped         | none           | none         |
| 1.8   | State:     | 1.9        | none             | none            | Playing         | none           | none         |
| 1.9   | State:     | 2.0        | none             | none            | Finished        | none           | none         |
| 2.0   | State:     | 2.1        | none             | none            | Skipped         | none           | none         |

...
It means that the control flow through Skipped port of Movie Clip node and False port of If node causes violation of the specification. Thus we can detect a bug stated in II-A.

III. TRANSLATION ALGORITHM

A. Translation Overview

An overview of the procedure for translating a visual script to an SMV program is shown below. Given specifications and node semantics, this translation procedure can be fully automated.

1) Declare SMV variables according to node semantics.
2) Describe control flows as transitions of input variables according to the graph structure.
3) Describe behaviors of nodes as transitions of output and state variables according to node semantics.
4) Describe changes of script variables according to node semantics.
5) Annotate specifications.

B. Variable Declaration

First we declare SMV variables according to given node semantics. As stated above, the SMV model of a visual script has four types of SMV variables.

input variables For each node, its input signal is represented as an input variable that has as its domain the name of its input ports and none denoting an undefined value. The initial value of an input variable is set to none.

output variables Similar to input variables, an output signal is represented as an output variable that has as its domain the name of its output ports and none. The initial value of an output variable is also set to none (except those of entry point nodes).

state variables In the case of a node with state transition, its internal state is represented as a state variable. The domain of the variable is exactly the set of internal states of the node. The initial value of the state variable of such node is defined based on its node semantics.

script variables A global variable is represented as a script variable. The domain of the variable is defined according to the node semantics that refer the change of the script variable.

As we stated in section II-A multiple nodes in a visual script can work in parallel. It means that a single node may also receive multiple input signals simultaneously. However, the definition of input variables described above assumes that a node receives only one input signal at the same time, in which case the other input signals are ignored. This might cause an incorrect behavior if some nodes are assumed to handle multiple input signals at the same time (fortunately these are very rare though). To avoid this problem, for nodes whose semantics require processing multiple input signals simultaneously, we define one input variable for each input port.

C. Translating Control Flow

In node-style visual script, its control flow is represented as propagation of signals through edges of the graph. Since signals are described as input and output variables, propagation of a signal between an input port and an output port is described as a change of the input variable based on the output variable. Thus in the SMV model, a control flow through edges is described as definitions of transitions of input variables.

Assume that the node NodeA has two input ports InA1 and InA2, each with edges to the output port OutB of the node NodeB and the output port OutC of the node NodeC. The transition of the input variable NodeAIn for the node NodeA is defined by the following steps:

1) Define the initial value of NodeAIn as none.
2) For each edge between the input port In and the output port Out, add the transition “If Out is activated then In will be activated in the next state” to the next description of NodeAIn.
3) Add the default transition rule that describes that any output ports are not activated.

The SMV program for the input variable NodeAIn is obtained as follows.

\[
\begin{align*}
\text{ASSIGN} \\
\text{init}(\text{NodeAIn}) &= \text{none}; \\
\text{next}(\text{NodeAIn}) &= \text{case} \\
&\quad \text{NodeBOut} = \text{OutB} : \text{InA1}; \\
&\quad \text{NodeCOut} = \text{OutC} : \text{InA2}; \\
&\quad \text{TRUE} : \text{NodeAIn}; \\
&\quad \text{esac};
\end{align*}
\]

All input variables can be automatically defined according to the graph structure of the visual script.

D. Specifying Node Semantics

As we stated in section II-B2, node semantics is defined as the transition relation of elements involved in the node. We now classify the node semantics to several types and show how to define the transition relation according to the type of node. Once the transition relation is obtained, it is easy to create templates for an SMV program from it.

Nodes are classified into those with a single output and those with multiple outputs. An entry point node is a special kind of node that has a single output. Nodes with multiple outputs are classified into those with conditional branches and those with internal states (or both).

1) Node with Single Output: A node with a single output port sends an output signal immediately upon receiving an input signal. Thus the node semantics of the node that has a single output port Out is defined as follows:

\[ \text{out}' = f_{\text{out}}(\text{in}) \]
\[ = \text{if } \text{in} \neq \text{none} \text{ then Out else none.} \]
An entry point node activates its output signal only in the initial state and not thereafter. Thus the node semantics of the node is defined as follows:

\[ \text{out}' \equiv \text{none}. \]

2) Node with Conditional Branches: Some nodes select output signals according to its conditional value. Since we do not consider data flow that affects the conditional value, we model the output signal to be selected non-deterministically. Thus the node semantics of the node that has \( n \) output ports \( \text{Out}_1, \text{Out}_2, \ldots \) and \( \text{Out}_n \) is defined as follows:

\[
\begin{align*}
\text{out}' & \equiv f_{\text{out}}(\text{in}) \\
& = \text{if } \text{in} \neq \text{none} \text{ then } \{\text{Out}_1, \text{Out}_2, \ldots, \text{Out}_n\} \\
& \quad \text{else none},
\end{align*}
\]

The transition relation of the node with three or more output ports can be defined similarly.

3) Node with State Transitions: Some nodes have internal states and send output signals depending on its internal state. The internal state transitions depending on the current state and the input signal. In most nodes, its output signal depends only on its internal state. Thus, regarding with the output signal, the node semantics of the node with state transitions has the following form:

\[
\begin{align*}
\text{out}' & \equiv f_{\text{out}}(\text{state}) \\
& = \text{if } \text{state} = \text{state}_1 \text{ then } \text{out}_1 \\
& \quad \text{else if } \text{state} = \text{state}_2 \text{ then } \text{out}_2 \\
& \quad \ldots \\
& \quad \text{else none},
\end{align*}
\]

where \( \text{out}_i \) denotes an output signal of the node, and \( \text{state}_i \) is the internal state in which the node sends the output signal \( \text{out}_i \). \( \text{out}_i \) can be a set of output signals to specify a non-deterministic choice on sending output signals.

Besides, in many cases, the next internal state is associated to either its input signal or the current internal state. Thus the node semantics for the internal state has the following form:

\[
\begin{align*}
\text{state}' & \equiv f_{\text{state}}(\text{in}, \text{state}) \\
& = \text{if } \text{in} = \text{in}_1 \text{ then } \text{state}'_1 \\
& \quad \text{else if } \text{in} = \text{in}_2 \text{ then } \text{state}'_2 \\
& \quad \ldots \\
& \quad \text{else if } \text{state} = \text{state}_1 \text{ then } \text{state}'_1 \\
& \quad \text{else if } \text{state} = \text{state}_2 \text{ then } \text{state}'_2 \\
& \quad \ldots \\
& \quad \text{else state}_n.
\end{align*}
\]

If the input signal is \( \text{in}_j \), then the internal state transitions to \( \text{state}'_j \). On the other hand, when the node has no input signal and its internal state is \( \text{state}_k \), the internal state transitions to \( \text{state}'_k \). Similar to \( f_{\text{out}}, \text{state}'_1 \) and \( \text{state}'_k \) can be a set of internal states to express a non-deterministic choice on state transition.

In the case of nodes with nondeterministic state transitions, such as \text{Movie Clip} node, only certain state transitions may continue to be selected. In the example of \text{Movie Clip} node, we allow a sequence in which its internal state continues to be Playing. However, such sequences often need to be excluded from the sequences to be checked. To avoid such a problem, we introduce a fairness constraint which restricts the scope of verification to only “fair” state transition sequences. Since our model intends that all nodes with state transitions eventually return to its initial state, we mechanically add for each state variable the fairness constraint that claims the state variable infinitely often has its initial value. By adding this constraint, the behavior where the node never returns to the initial state is not considered in verification by NuSMV. Returning to the example of \text{Movie Clip} node, we add the constraint by using \text{FAIRNESS} description to guarantee that the state variable \text{MovieClip3State} infinitely often has its initial value \text{Stopped} (see Fig. 4).  

4) Node with Custom Semantics: Some nodes do not follow the form described above, and their output signals and internal states are determined according to semantics specific to the node. We need to provide \text{custom semantics} for such nodes. In general, custom semantics can be described in the following form:

\[
\begin{align*}
\text{out}' & \equiv f_{\text{out}}(\text{in, state}) \\
& = \text{if } \text{cond}_1(\text{in, state}) \text{ then } \text{out}_1 \\
& \quad \text{else if } \text{cond}_2(\text{in, state}) \text{ then } \text{out}_2 \\
& \quad \ldots \\
& \quad \text{else none},
\end{align*}
\]

\[
\begin{align*}
\text{state}' & \equiv f_{\text{state}}(\text{in, state}) \\
& = \text{if } \text{cond}_1(\text{in, state}) \text{ then } \text{state}_1 \\
& \quad \text{else if } \text{cond}_2(\text{in, state}) \text{ then } \text{state}_2 \\
& \quad \ldots \\
& \quad \text{else state}_n,
\end{align*}
\]

where \( \text{cond}_i(\text{in, state}) \) is the condition over the input signal and the internal state.

E. Representing Script Variables

Script variables represent global variables used in visual scripts and states of external components that visual scripts interact. By defining script variables and describing the conditions for those variables, we can verify those conditions with NuSMV. Note that we need not to define all the variables in visual scripts, but minimum variables that we want to verify in the specification.

Since script variables can be modified by multiple nodes, it is necessary to integrate their transition relations defined in each node semantics into a single transition relation in order to represent their behavior. Assume that the script variable \( \text{var} \) can be modified by the node \( \text{NodeA} \) and \( \text{NodeB} \), and their node semantics specify that \( \text{var} \) changes to the same value.
val in conditions cond_A for NodeA and cond_B for NodeB as follows:

\[ \text{var}' \equiv \text{if } \text{cond}_A\left(\text{in}_A, \text{state}_A, \text{var}\right) \text{ then val, and} \]
\[ \text{var}' \equiv \text{if } \text{cond}_B\left(\text{in}_B, \text{state}_B, \text{var}\right) \text{ then val.} \]

Then we can integrate those transition relations into the following single relation:

\[ \text{var}' \equiv \text{if } \text{cond}_A\left(\text{in}_A, \text{state}_A, \text{var}\right) \text{ or } \text{cond}_B\left(\text{in}_B, \text{state}_B, \text{var}\right) \text{ then val.} \]

F. Scope and Limitations

1) Soundness: Strictly speaking, the behavior of our model is not completely equivalent to the actual behavior of the target visual scripts. This difference may result in false positives or false negatives in verification. These problems arise due to differences in the time required for signal propagation and abstractions in the modeling of external components.

signal propagation Even if signal propagation is not time-consuming in the visual script implementation, it takes at least one step of state transition to propagate a signal in our model. This leads to a case where a particular one of several control flows, which are to be completed simultaneously (or whichever may be finished first), will always be completed first in the model. As a result, errors that occur only in a particular control flow may be overlooked.

For example, the following two control flows may occur in the script of Fig. 3:
- Movie Clip: Finished → Set Event Mode: Disable, and
- Movie Clip: Skipped → If: True → Set Event Mode: Disable.

Although both will be completed at the same time in the actual implementation, the former will always be completed faster than the latter in our model.

external components Our model does not consider the detailed behavior of external components. This is because the behavior of external components is often not fully documented and it is difficult to properly model such behavior. In such cases, nondeterminism can be used to abstractly represent the behavior of external components.

For example, the Movie Clip node in Fig. 3 skips or finishes the playback of the movie depending on the behavior of the external components such as movie player application and game player’s input. We model the behavior as a state transition where Playing changes to one of the states (Playing, Finished, Skipping) non-deterministically. A similar abstraction is used in the definition of node semantics that depend on data flow as shown in III-D2.

This abstraction causes the model to include behaviors that do not exist in the actual script, which may result in pseudo-counterexamples.

2) Coping with State Explosion: If we model a huge visual script as it is, its state space grows exponentially, resulting in a state explosion. Therefore, it is necessary to reduce the size of the model by appropriately partitioning and abstracting the script according to the properties to be checked. The number of variables in an SMV model have a large impact on the size of the state space to be searched. In the next section, we will discuss a model optimization to reduce the number of variables in an SMV model.

3) Scope of Verification: By modeling rigorously, many of the above problems related to soundness can be avoided. However, rigorous modeling increases the model size, which leads to state explosion, and we accept this risk in our verification framework. In fact, our method currently aims at detecting obvious mis-descriptions of visual scripts as stated in II-A, and this risk is not considered to be a practical problem. We will discuss this issue in Section V.

IV. STATE SPACE REDUCTION BY OPTIMIZING MODEL

As the size of the node graph increases, the models generated also become larger, making it difficult to perform verification in a realistic amount of time. To finish the verification process in realistic time, optimization of the model for state space reduction is required. Since the size of state space increases exponentially with the number of SMV variables, our optimization focuses on how to reduce the number of SMV variables.

A. Remove Nodes without Side Effects

Observation on the scripts written in our game development shows that most of the nodes have the following characteristics:

- Many nodes have multiple inputs and single output.
- Many nodes send an output signal after receiving an input signal without side effects such as sending data flow signals or changing values of global variables.

We refer such nodes as NoSE nodes. NoSE node can be removed from the node graph by directly reconnecting the ports connected to its input ports with the port connected to its output port.

For example, Fig. 8 (a) shows the node graph which has two NoSE nodes NoSE1 and NoSE2. In this case, we first remove the NoSE1 node by reconnecting Out4 of Node2 and Out4 of Node3 with inB of NoSE2 and in2 of Node5. Then we remove the NoSE2 node by Out3 of Node1 and the two ports connected to its inB port with in1 of Node4. Thus we can obtain the node graph shown in Fig. 8 (b).

Since the number of SMV variables is proportional to the number of (ports of) nodes, the number of SMV variables can be greatly reduced by removing those many harmless nodes.

Strictly speaking, applying this optimization can slightly change the behavior of the model for the same reason as stated in III-F. We also accept this risk by the same reason.
B. Encode State Transition to Output Variable

We explained how our method handle state transition of nodes in [II-D3]. However, this increases the number of SMV variables and makes a negatively impact to the verification performance. We will explain the optimization that embeds the state transition of the node to the output variable, and show that it can reduce the number of SMV variables.

As stated in [II-B2] the node semantics is generally expressed as the following formulas:

\[\begin{align*}
    \text{out}' &\equiv f_{\text{out}}(\text{in}, \text{state}), \\
    \text{state}' &\equiv f_{\text{state}}(\text{in}, \text{state}).
\end{align*}\]  

The value of the output signal only depends on its internal state in the node with state transition. Furthermore, if we were strictly represent the behavior of the node, the output signal should change immediately according to the change of internal state. We can thus obtain the following relation instead of [1]:

\[\text{out} \equiv f_{\text{out}}(\text{state}).\]  

We focus on the fact that the internal state is associated with the value of the output signal shown in [3]. Therefore, by representing the internal state using the value of the output signal, the state variable can be removed from the equation. The basic idea of this optimization is the following derivation:

1) Apply the inverse function of \(f_{\text{out}}\) to both sides of the equation [5]

\[\text{state} \equiv f_{\text{out}}^{-1}(\text{out})\]  

2) Substitute [4] for [2]

\[f_{\text{out}}^{-1}(\text{out}') \equiv f_{\text{state}}(\text{in}, f_{\text{out}}^{-1}(\text{out}))\]  

3) Apply \(f_{\text{out}}\) to both sides of the equation [5]

\[\text{out}' \equiv f_{\text{out}}(f_{\text{state}}(\text{in}, f_{\text{out}}^{-1}(\text{out})))\]  

As shown in [6] we can replace state variables with output variables with this derivation. We thus can reduce the number of SMV variables.

Since \(f_{\text{out}}\) is a surjective function, but not an injective function, we can not define the inverse function of \(f_{\text{out}}\). Then, we define a bijective function \(g_{\text{out}}\) by extending \(f_{\text{out}}\). When an output signal is associated to multiple internal states, we duplicate the output signal in order to associate them with single internal state. The duplicated signal of \(\text{out}\) associated to the state \(\text{state}\) is referred as \(\text{out}_{\text{state}}\). We define the bijective function \(g_{\text{out}}\) as follows:

\[g_{\text{out}}(\text{state}) = \begin{cases} 
\text{out} & \text{if for all internal states } t, \\
\text{state} \neq t \rightarrow f_{\text{out}}(\text{state}) \neq f_{\text{out}}(t) & \text{out}_{\text{state}} \\
& \text{otherwise}
\end{cases}\]  

where \(\text{out} = f_{\text{out}}(\text{state})\). \(\text{out}_{\text{state}}\) is a newly defined value that is different from \(\text{out}\), but is treated in the same way as \(\text{out}\).

Using the bijective function \(g_{\text{out}}\), we can redefine the formula [6] as follows:

\[\text{out}' \equiv g_{\text{out}}(f_{\text{state}}(\text{in}, g_{\text{out}}^{-1}(\text{out})))\]  

We refer this function as \(h_{\text{out}}(\text{in}, \text{out})\).

For example, the transition relation \(f_{\text{out}}(\text{state})\) and \(f_{\text{state}}(\text{in}, \text{state})\) of the Movie Clip node is defined as follows:

\[f_{\text{out}}(\text{state}) = \begin{cases} 
\text{Finished} & \text{if } \text{state} = \text{Finished} \\
\text{Skipped} & \text{if } \text{state} = \text{Skipped} \\
\text{none} & \text{else}
\end{cases}\]  

\[f_{\text{state}}(\text{in}, \text{state}) = \begin{cases} 
\text{Playing}, \text{Finished}, \text{Skipped} & \text{if } \text{in} = \text{Start} \\
\text{none} & \text{if } \text{state} = \text{Playing} \\
\text{none, none} & \text{if } \text{state} = \text{none}
\end{cases}\]  

We can obtain \(g_{\text{out}}\) and \(g_{\text{out}}^{-1}\) from \(f_{\text{out}}\) as follows:

\[g_{\text{out}}(\text{state}) = \begin{cases} 
\text{none}_\text{stopped} & \text{if } \text{state} = \text{Stopped} \\
\text{none}_\text{playing} & \text{if } \text{state} = \text{Playing} \\
\text{Finished} & \text{if } \text{state} = \text{Finished} \\
\text{Skipped} & \text{if } \text{state} = \text{Skipped}
\end{cases}\]  

\[g_{\text{out}}^{-1}(\text{out}) = \begin{cases} 
\text{Stopped} & \text{if } \text{out} = \text{none}_\text{stopped} \\
\text{Playing} & \text{if } \text{out} = \text{none}_\text{playing} \\
\text{Finished} & \text{if } \text{out} = \text{Finished} \\
\text{Skipped} & \text{if } \text{out} = \text{Skipped}
\end{cases}\]  

Finally we can obtain the optimized transition relation \(h_{\text{out}}(\text{in}, \text{out})\) as follows:

\[h_{\text{out}}(\text{in}, \text{out}) = \begin{cases} 
\text{none}_\text{playing} & \text{if } \text{in} = \text{Start} \\
\text{none}_\text{none} & \text{if } \text{out} = \text{none}_\text{playing} \\
\text{none}_\text{none} & \text{if } \text{out} = \text{none}_\text{none} \\
\text{none}_\text{none} & \text{if } \text{out} = \text{none}_\text{none}
\end{cases}\]
In addition, we need to modify the set of initial values of the output signal. We refer the set as $I_{out}$. Since the internal state of the node is identified by the value of its output signal, $I_{out}$ is defined from the set of initial values of internal states of the node $I_{state}$ and $g_{out}$ as follows:

$$I_{out} \equiv \{ g_{out}(s) \mid s \in I_{state} \}.$$  \hspace{1cm} (8)

Fig. 9 shows the model that we applied this optimization to the Movie Clip node. As you can see, we can remove the state variable MovieClip3State.

| VAR |
|-----|
| MovieClip3In : {none, Start}; |
| MovieClip3Out : {none_Stopped, none_Playing, Finished, Skipped}; |
| ASSIGN |
| 5 init(MovieClip3Out) := none_Stopped; |
| 6 next(MovieClip3Out) := case |
| 7 MovieClip3In = Start : none_Playing; |
| 8 MovieClip3Out = none_Playing : {none_Playing, Finished, Skipped}; |
| 9 TRUE : none_Stopped; |
| 10 esac; |

![Fig. 9. Optimized Movie Clip node model](image)

V. PRELIMINARY EVALUATION

For a preliminary evaluation, we implemented a prototype and applied it to the visual scripts that are used in the production for FFXVand perform flag management. Seven scripts (#1 - #7) were randomly selected, and one very large script (#8) was arbitrarily selected to clarify the limit of script size to which our method can be applied. All of these scripts handle the event mode flag, and we checked the property that if the flag is true, it must eventually become false. The CTL formula annotated in the SMV model is the same as the one shown in [11-B1]. We also applied the proposed optimization to reduce the size of the SMV models.

A. Node Semantics

We prepared an encoding by SMV language for each node in the scripts. As stated in section [11-B2], we can straightforwardly prepare an encoding for nodes with simplified semantics. The eight scripts shown in Table I have 1,178 nodes in total. There are 164 kinds of those nodes, which are classified as follows:

1) node with single output: 98 kinds of nodes.
2) node with conditional branches: 7 kinds of nodes.
3) node with state-transition: 14 kinds of nodes.
4) node with conditional branches and state-transition: 12 kinds of nodes.
5) entry point node: 3 kinds of nodes.
6) node with custom semantics: 30 kinds of nodes.

Nodes classified from 1) to 5) can be modeled by using a common node semantics for each classification. Additionally we have prepared custom semantics for 30 kinds of nodes in 6). In the end, we can convert 1,178 nodes to SMV models by manually preparing only 30 types of node semantics (furthermore, these node semantics may be reused). This result demonstrates that our translation method has enough availability in practical use.

B. Verification Results

Table I shows the results of the evaluation. The column descriptions are the following:

- # of nodes: The number of visual script nodes in the target script.
- # of vars: The number of SMV variables in the generated SMV model.
- reachable states: The number of reachable states reported by NuSMV.
- eval. time: Execution time of NuSMV for the model. We tried 5 times for each script and adopted a median value of those trial.
- detected?: Whether NuSMV detected a problem in the script or not.

We can detect the bugs on two scripts #5 and #7 and can obtain the counterexamples. As you can see, we can significantly reduce the verification time by applying the optimization. However, the verification of #8 was not completed within the 3 hours set as the timeout.

C. Discussion

1) soundness: We found counterexamples on two scripts #5 and #7 during the experiments. We confirmed with the game designers that those counterexamples are not false positive and indicate real bugs in the scripts. This result demonstrates that our method can detect the specific types of bugs that we are focusing on.

2) optimization effectiveness: By applying the optimization, we can considerably reduce the state space to be checked and the verification cost. Particularly we can decrease the verification time by 98.1% in the case of #1. Besides, the effect of optimization in the two cases where the script bugs were detected is greater than in the other scripts. This result suggests that the effect of optimization is greater in terms of bug detection.

3) state explosion: This result showed that even with optimization, it is difficult to handle very large scripts in our framework. By partitioning the node-graph according to the structure of the control flow and applying further abstraction, we expect that it is possible to reduce the state space and achieve verification in a realistic amount of time even for such a large script. Improving our algorithm to handle those large scripts is future work.

VI. SUMMARY AND FUTURE WORK

We described an automatic verification method for node-based visual script notation for efficient game production. Our method automatically converts visual script implementation 2According to the game designers, those scripts are used only in the trial version, so they will not fix the bugs though.
with node semantics to the input model for NuSMV. Preliminary evaluations confirmed that for most of the visual scripts used in the production of FFXV, we could detect the specific types of bugs we were focusing on in a realistic amount of time.

However, it appears that there are some very large scripts used in the production for FFXV, that our method cannot handle. Thus a next step for improving our work would be applying compositional verification technique [20]. If the node graph can be partitioned into multiple subgraphs, and each subgraph can be verified separately, then the verification cost can be reduced and the verification can be completed in a realistic time. In addition, compositional verification also may allow for the verification of game logic written as multiple scripts. Currently, we can verify only scripts written as a single node graph. If multiple scripts can be verified together, the control flow between scripts can be tracked, resulting in a reduction of false positives and false negatives. Another next step would be the automated generation of node semantics from the script implementation. Currently, we need to write node semantics manually. If we can extract node semantics from its implementation, we can increase the range of automation of our method.

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