Inferring Automata Logic From Manual Control Scenarios: Implementation in Function Blocks

Daniil Chivilikhin*, Anatoly Shalyto*, and Valeriy Vyatkin†
*Computer Technologies Laboratory, ITMO University, Saint Petersburg, Russia
Email: chivdan@rain.ifmo.ru, shalyto@mail.ifmo.ru
†Department of Electrical Engineering and Automation, Aalto University, Finland
Email: vyatkin@ieee.org

***Abstract*—This paper presents an automated technique for inferring finite automata logic from behavior examples derived from the interaction of the user and the controlled object model. The technique is demonstrated for IEC 61499 function blocks. We show how to automatically generate a manual control Human-Machine Interface (HMI) for Model-View-Control applications and how to use the HMI to record behavior examples. We also suggest a polynomial-time algorithm for constructing Execution Control Charts (ECCs) of basic FBs from behavior examples. The use of the proposed technique is illustrated on an example.**

I. Introduction

Automata are widely used in industrial automation, both in legacy IEC 61131 programs and in function block applications in IEC 61499. The development of automata-based controllers is a hard, time-consuming process, especially when the problem requires automata with a large number of states and complex logic.

In this paper we propose an automated approach that can help engineers create automata for control applications developed following the Model-View-Controller (MVC) design pattern. Assuming that the Model and View are implemented, we present an automated technique for creating an automaton representing the Controller. The proposed approach is demonstrated on the example of IEC 61499[1], which is a rather new standard in industrial automation that defines an open architecture for developing distributed control and automation systems. The main structural elements of IEC 61499 applications are *function blocks* (FBs), which encapsulate both logic and data flows. FBs can be either *basic* or *composite*. A *basic* FB is defined by an *Execution Control Chart* (ECC), which is a special type of a Moore finite-state machine. A *composite* FB is represented by a network of other FBs, either basic or composite. Regardless of the concrete type, any FB is characterized by an *interface*, which defines input/output events and input/output vairables.

MVC is quite a common design pattern for IEC 61499 [1], [2], [3]. For example, in [1] the following guideline for IEC 61499 MVC application development is suggested. First, the View is created which implements a visualization of the designed system. Second, one creates the Model using the View for debugging it. Finally, the Model and the View are used for (manually) developing and verifying the Controller.

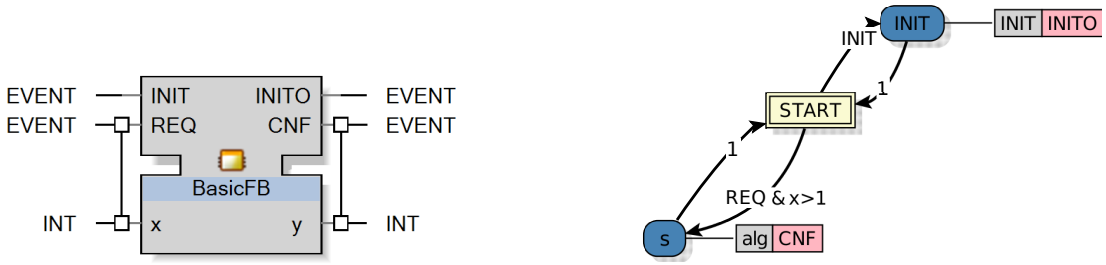
The new approach proposed in this paper allows to omit the last part, delegating the creation of the Controller to an automated procedure. At the first step of the proposed approach the FB application is augmented with a Human-Machine Interface (HMI) to allow the user to perform manual control of the Model. Secondly, the FB application is automatically modified to allow logging of user input and model behavior. At the third step, the user acts as a controller for the Model in a series of test cases. The behavior of the user and the resulting actions of the model are recorded and saved. Finally, at the fourth step we use the proposed polynomial-time algorithm to automatically construct an ECC that models the recorded behavior. The constructed ECC is able to reproduce the control actions the user performed when processing test cases. At the moment, results are limited to constructing ECCs which have only Boolean input and output variables.

II. Related Work

Problems related to inferring various types of automata from behavior examples attracted a substantial amount of research over the years. Deterministic finite automata can be efficiently inferred from labeled strings using SAT-solvers [4], though the problem is known to be NP-hard [5]. Finite-state transducers can be inferred from examples using evolutionary algorithms [6]. Extended finite-state machines can be inferred from scenarios using SAT-solvers [7]. Metaheuristic algorithms have been used for inferring finite-state machines for controlling an unmanned aircraft [8].

An approach has been proposed for reconstrucing basic IEC 61499 function block logic from execution scenarios [9]. The algorithm proposed in that paper is a metaheuristic one, i.e. there are no theoretical bounds on its run time. In the current paper we found that if each state algorithm is used in exactly one state of the ECC, a polynomial-time algorithm is sufficient to infer an ECC from execution

[1]V. Vyatkin, IEC 61499 Function Blocks for Embedded and Distributed Control Systems Design, 2nd Edition, ISA 2012



(a) Function block interface example

(b) Execution control chart example

Figure 1. Examples of a function block interface (left) and execution control chart (right)

scenarios.

III. IEC 61499 Standard

Applications in the IEC 61499 are represented in the form of a network of interconnected FBs. Each FB has an *interface*, which defines possible input/output events and input/output variables. Variables can be, for example, Boolean, integer, or real, and can be associated with input and output events.

Basic FBs are represented by ECCs, which are Moore finite-state machines. An ECC is a set of *states* connected with *transitions*. At any moment in time the ECC is in a particular state. When an input event is received, the ECC switches to another state if a *guard condition* (in this work, a Boolean formula over input variables) on one of the transitions is satisfied. Transitions are checked in the order they are listed in the FB source file; the first transition for which the guard condition is satisfied is triggered.

An ECC state can have a list of associated *actions*. Each action can include an *algorithm* and/or an *output event*. When the ECC makes a transition to a state, the list of actions is executed. State algorithms are, most commonly, implemented using the *Structured Text* language and used, e.g., for setting output variables values. An example of an FB interface is shown in Fig. 1a, associations of events with variables are depicted by vertical lines. An example of an ECC is shown in Fig. 1b.

In this work we consider ECCs that have only Boolean input and output variables. We also assume that guard conditions only depend on input variables. Under this assumption, an execution control chart is defined as an eight-tuple $\langle Y, EI, X, EO, Z, y_0, \phi, \delta \rangle$, where Y is a finite set of states, EI is a set of input events, X is a set of Boolean input variables, EO is a set of output events, Z is a set of Boolean output variables, $y_0 \in Y$ is the initial state, $\phi \colon Y \times EI \times 2^X \to Y$ is the transitions relation and $\delta \colon Y \to (\{0,1\}^{|Z|} \to \{0,1\}^{|Z|}) \times EO$ is the outputs relation. The outputs relation defines that each state is associated with an action, which can include a so-called algorithm and an output event. In our simplified case algorithms are functions over output variables that transform a Boolean string to another Boolean string. It is assumed that the initial state $y_0 = 0$.

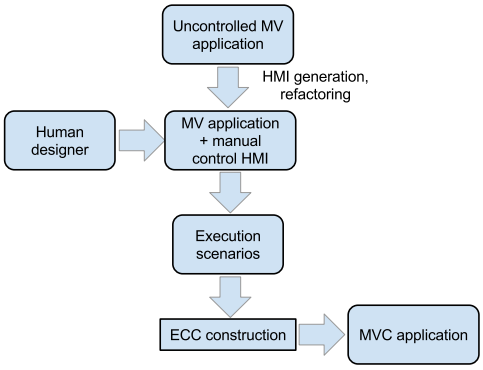


Figure 2. General scheme of the proposed approach

IV. Proposed Approach

We make the following additional assumptions in our approach.

- The FB application is designed following the Model-View-Controller (MVC) pattern and the Model and View implementations are available.
- The desired Controller is a basic FB with Boolean input and output variables.
- $M.O$ is the set of the Model's output variables that should be used for the Controller's input.
- $M.I$ is the set of the Model's input variables that should be derived from the Controller.

The proposed approach includes the following steps shown on the scheme in Fig. 2.

1) **Manual control HMI generation**. Generate FBs implementing manual control for selected output variables of the target FB.
2) **Refactoring for enabling logging**. Refactor the FB application to support execution scenarios recording.
3) **Execution scenarios recording**. Record execution scenarios from user input and model behavior.
4) **Inferring ECC from scenarios**. Attempt to infer an ECC consistent with recorded execution scenarios.

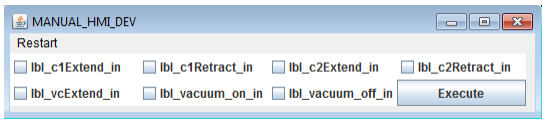


Figure 3. An example of the generated HMI for the PnP system

A. Manual control HMI generation

The manual control is a separate HMI and is comprised of a set of checkboxes (one per each variable from $M.I$) and an "Execute" button. A checked box corresponds to the output variable being *true*, an unchecked box means that the corresponding variable is *false*. Given the set of output variables, all FBs implementing the HMI are generated automatically using a *bash* script and corresponding FB source file templates. A total of six FBs are generated and two more FBs are altered. An example of a generated manual control HMI is shown in Fig. 3.

A dummy FB representing the Controller is generated. Its set of input variables is $M.I \cup M.O$, and its set of output variables is $M.I$. Model outputs $M.O$ are connected with corresponding controller inputs. $M.I$ variables are also connected to the inputs of the controller. Controller outputs are connected with corresponding Model inputs. When the user presses the "Execute" button, the *EXEC* event is generated, which is connected to the *REQ* input event of the Controller.

B. Refactoring for enabling logging

An *execution scenario* s is a list of *execution scenario elements* s_i, where each element consists of an input event $e^{\text{in}} \in EI$, a set of input variable values $\text{in} \in \{0,1\}^{|X|}$, a set of output variable values $\text{out} \in \{0,1\}^{|Z|}$, and, optionally, an output event $e^{\text{out}} \in EO$. For example, if the FB interface defines one input event REQ, three input variables, two output variables, and one output event CNF, then

$$\langle REQ, 000, 00, CNF\rangle, \langle REQ, 001, 01, CNF\rangle, \langle REQ, 101, 11, CNF\rangle$$

is an execution scenario.

In order to record execution scenarios from the user's interaction with the manual control HMI, a refactoring of the FB application is automatically performed. The dummy Controller FB generated on the previous step is replaced with a composite *ProxyLogger* FB; all input and output connections are copied. The *ProxyLogger* FB network includes three FBs: *InputLogger*, the Controller FB, and *OutputLogger*. When an input event is received by *ProxyLogger*, it is passed on to *InputLogger*, which logs the input event and the current values of input variables. The event and input variable values are passed on to the Controller FB. The *OutputLogger* FB does the same with output variable values and output events. An example of the FB network of a *ProxyLogger* FB is shown in Fig. 4.

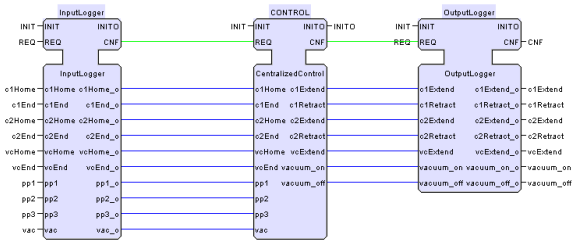


Figure 4. An example of a *ProxyLogger* function block

C. Execution scenarios recording

At this step the generated HMI is used to perform manual control of the system. When the user wants to change the values of output variables, he ticks corresponding checkboxes on the HMI and presses the "Execute" button. Here we assume that after the button has been pressed, the model uses a limited amount of time to perform actions triggered by changed variables values. After all actions have been performed and the system has converged to some steady state, the manual control HMI can be used again.

D. Inferring an ECC from scenarios

In this section we describe the proposed polynomial-time algorithm for constructing an ECC from execution scenarios. The algorithm works correctly under the assumption that each state algorithm is used in exactly one state of the resulting ECC. Examining existing IEC 61499 applications revealed that a large class of basic FBs satisfy this assumption. The main idea is that under the taken assumption it is possible to automatically determine the minimal possible set of Boolean algorithms that are sufficient to describe given execution scenarios. This set of algorithms defines the states of the sought ECC. The algorithm includes the following main steps:

1) determine the minimal set of state algorithms;
2) construct an ECC from scenarios labeled by found algorithms;
3) simplify the constructed ECC.

1) Algorithm representation: Algorithms are represented in the form of strings of length $|Z|$ over the alphabet {"0","1","x"}. Let a_i be the algorithm associated with state y_i. The j-th character of the algorithm is associated with the j-th output variable. Algorithms have the following semantics:

- $a_i^j =$ "0": set $z_j \leftarrow 0$;
- $a_i^j =$ "1": set $z_j \leftarrow 1$;
- $a_i^j =$ "x": preserve current value of z_j.

To calculate the result of applying an algorithm a to a set of variable values z we will use the function $\text{applyAlg}(z, a)$.

2) Determining the minimal set of state algorithms: Let A be a set of algorithms. Initially, A is empty. Firstly, for each scenario s and each two consequent scenario elements s_i and s_{i+1} we add to A an algorithm that transforms $s_i.\text{out}$ to $s_{i+1}.\text{out}$. Such an algorithm is calculated using the calcAlg function. Secondly, we try to minimize A by merging each pair of algorithms, if possible.

Before merging algorithms a and b we first check if they are *consistent*. Algorithms a and b are inconsistent if at some position they have contradicting elements, i.e. $\exists i : a_i = 0, b_i = 1$ or $a_i = 1, b_i = 0$. For example, algorithms $x01$ and $10x$ are not inconsistent, but algorithms $a = x00$ and $b = x10$ are, since $a_1 = 0$ and $b_1 = 1$. Inconsistent algorithms cannot be merged.

To calculate the merge m^{ab} of two algorithms a and b we use the function merge(a, b) which works according to the following formula:

$$m_i^{ab} = \begin{cases} a_i, & \text{if } a_i = b_i; \\ \text{“x”}, & \text{if } a_i = \text{“x” or } b_i = \text{“x”}. \end{cases} \quad (1)$$

Next, we remove a and b from A and add to A the merged algorithm m^{ab}. Then we run through all scenarios and check if the merged algorithm m^{ab} can be used instead of both a and b. We check all pairs of scenario elements s_i and s_{i+1} such that the algorithm that transforms $s_i.\text{out}$ to $s_{i+1}.\text{out}$ is either a or b. If the usage of m^{ab} results in the same output variable values as when using algorithm a (b) for all such pairs of scenario elements, then the merge is retained. Otherwise the merge is rejected, m^{ab} is removed from A, a and b are added back to A.

The process is repeated until no more merges can be performed. The resulting set of algorithms is, by construction, the minimal possible set of algorithms that can be used to represent given execution scenarios. This step runs in $O(N + N \cdot \hat{A}^3) = O(N \cdot \hat{A}^3)$, where $N = |S|$ is the total number of scenario elements and $\hat{A}$ is the initial number of elements in A. Since, in the worst case, $\hat{A} = 3^{|Z|}$, we get a final time complexity of $O(N \cdot 3^{|Z|^3})$. The algorithm is summarized in Algorithm 1. Note that since the initial set of Boolean algorithms is finite and each merge reduces the size of the set, this algorithm eventually terminates.

3) Constructing an ECC: Having determined the minimal set of state algorithms A, we can now use this set to construct an ECC from given execution scenarios. Let A_{used} be the list of used algorithms (initially, it is empty) and $\{\tau_i\}_{i=0}^{|A|-1}$ be a list of lists of transitions. First, we determine the algorithm $a_0 \in A$ that is consistent with the first element of all scenarios meaning that applyAlg$(s_0.\text{out}, a_0) = s_1.\text{out}$ for all $s \in S$. The algorithm a_0 is added to A_{used}.

Then, we iterate over all scenarios. For each scenario, the current state y_{current} is initially 0. We iterate over scenario elements and at each step consider elements s_i and s_{i+1}. If $s_i.\text{out}$ equals $s_{i+1}.\text{out}$, we increment i and move on. If not, we select an algorithm a from A such that applyAlg$(s_i.\text{out}, a)$ equals $s_{i+1}.\text{out}$.

If $a \in A_{\text{used}}$ then the new state y_{new} is the position of a in A_{used}. Otherwise, a is added to A_{used} and y_{new} is $|A_{\text{used}}| - 1$. Then we add to $\tau_{y_{\text{current}}}$ a new transition labeled with the input event $s_{i+1}.e^{\text{in}}$, set of input variable values $s_{i+1}.\text{in}$, and the destination state y_{new}. Here we also check that if $\tau_{y_{\text{current}}}$ already contains a transition labeled with $s_{i+1}.e^{\text{in}}$ and $s_{i+1}.\text{in}$, then the destination state has to be equal to y_{new}. If the destination state of the old transition is different from y_{new}, then the algorithm prints a message that scenarios contain a nondeterministic behavior and aborts. Finally, the current state is updated: $y_{\text{current}} \leftarrow y_{\text{new}}$. After all scenarios have been processed, the ECC states are assigned the corresponding algorithms and output events. This step runs in $O(N)$. The ECC construction algorithm is summarized in Algorithm 2.

4) Simplifying the constructed ECC: In order to simplify and generalize the ECC constructed in the previous step, we will use the same representation of ECCs as in [9]. An ECC is represented as a set of states Y, where each state y_i has a set of transition groups T_i per each input event, and an associated action, which consists of an algorithm and an output event. Each transition group $t \in T_i$ has an associated Boolean array called the input variable significance mask m_t and a transition table Φ_t of $1 \times 2^{\Sigma m_t}$ elements, where

Algorithm 1 Minimal Boolean algorithm set construction

```
1:  A = new Set()
2:  for all scenarios s ∈ S do
3:    for i = 0 to |s| − 1 do
4:      A ← A ∪ {calcAlg(s_i.out, s_{i+1}.out)}
5:    end for
6:  end for
7:  while true do
8:    changed ← false
9:
10:   for all a ∈ A do
11:     for all b ∈ A, b ≠ a do
12:       m^ab ← merge(a, b)
13:       if merge is valid then
14:         A ← A \ {a, b}
15:         A ← A ∪ {m^ab}
16:         changed ← true
17:         goto line 21
18:       end if
19:     end for
20:   end for
21:   if ¬ changed then
22:     break
23:   end if
24: end while
25: return A
```

Algorithm 2 ECC construction

Require: A – minimal set of Boolean algorithms
τ – list of lists of transitions
A_{used} – list of used algorithms
$A_{\text{used}} \leftarrow \{a \in A : \forall s \in S \text{ applyAlg}(s_0.\text{out}, a) = s_1.\text{out}\}$
for all $s \in S$ **do**
  for $i = 0$ to $|s| - 1$ **do**
    $y_{\text{current}} \leftarrow 0$
    if $s_i.\text{out} = s_{i+1}.\text{out}$ **then**
      continue
    end if
    $a \leftarrow \text{getBestMatch}(s_i.\text{out}, s_{i+1}.\text{out}, A)$
    $y_{\text{new}} \leftarrow -1$
    if $a \in A_{\text{used}}$ **then**
      $y_{\text{new}} \leftarrow A.\text{indexof}(a)$
    else
      $A_{\text{used}} \leftarrow A_{\text{used}} \cup \{a\}$
      $y_{\text{new}} \leftarrow |A_{\text{used}}| - 1$
    end if
    t = new Transition($s_{i+1}.e^{\text{in}}$, $s_{i+1}.\text{in}$, y_{new})
    if $t \notin \tau_{y_{\text{current}}}$ **then**
      $\tau_{y_{\text{current}}} \leftarrow \tau_{y_{\text{current}}} \cup \{t\}$
    end if
    if nondeterministic behavior **then**
      print "Nondeterministic behavior"
      exit
    end if
    $y_{\text{current}} \leftarrow y_{\text{new}}$
  end for
end for

Σm_t is the number of elements in m_t that are *true*. If $m_t^i = true$ variable x_i is called *significant*, otherwise, it is called *insignificant*. Each j-th element of Φ_t stores the new state for that transition. For example, if there are four significant input variables x_0–x_3, Φ_t^5 stores the new state that the ECC has to change to when $(x_0, x_1, x_2, x_3) = (0, 1, 0, 1)$ since $0101 = 2^5$.

The result of the previous step is an ECC represented by $\{\tau_i\}_{i=0}^{|A|-1}$, in which the number of transition groups in each state equals the number of transitions in this state, and in each transition group all variables are significant. Such a solution can be extremely large (in the worst case, the number of transitions equals the number of scenario elements) and redundant. Therefore, we apply the same simplification procedure as the one used in [9].

We attempt to delete each significant input variable of each transition group according to the following algorithm. The selected input variable is made insignificant $m_i \leftarrow false$, the size of the transition table is halved. We randomly select which of the two old transitions to preserve (the one with $x_i = true$ or $x_i = false$). If the changed model is still able to correctly process all execution scenarios, the change is retained, otherwise it is rejected. The process is repeated until no more changes can be made. This step takes $O(N)$ time.

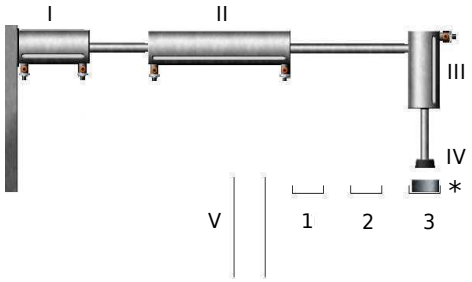


Figure 5. Screenshot of one the Pick-and-Place manipulator system implementations

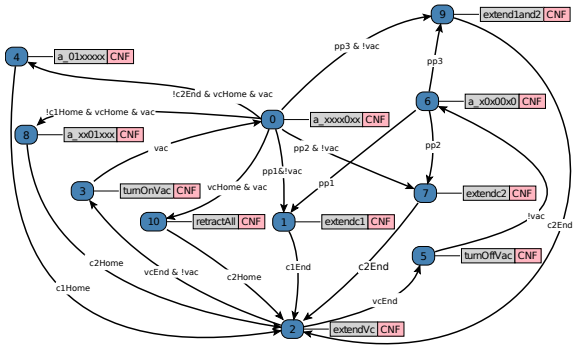


Figure 6. Inferred ECC model

V. Usage Example

In this section we describe an example of how the proposed technique can be used to infer FB logic. The example is based on the Pick-and-Place (PnP) manipulator project [10]. The project is implemented in the MVC framework and the Controller is a basic FB with Boolean input and output variables. The FBDK[2] development environment has been used for recording execution scenarios and post-experiment simulation.

A. Pick-and-Place manipulator system

A screenshot of the PnP system is shown in Fig. 5. We considered an implementation with a suction unit (IV) for picking up work pieces and three pneumatic cylinders: two horizontal cylinders (I, II) and one vertical cylinder (III). The system also has three sensors for determining whether a new work piece appeared in one of the three input trays (1, 2, 3). Cylinders are used to move the suction unit in position of the new work piece, pick it up and move to the output slider (V).

[2]http://www.holobloc.com/doc/fbdk

In this implementation of the PnP manipulator, logic control is performed by a single basic FB *CentralizedControl*. It receives signals when work pieces appear in the input trays and sends commands to other FBs that control the movement of the cylinders and the suction unit. The interface of the *CentralizedControl* FB is shown in the center of Fig. 4. It defines ten Boolean input variables: c1Home/c1End (cylinder I is in the leftmost/rightmost position), c2Home/c2End (cylinder II is in the leftmost/rightmost position), vcHome/vcEnd (cylinder III is in the top/bottom position), pp1/pp2/pp3 (a work piece is present in input tray 1/2/3), vac (the suction unit is on). Seven output variables are used: c1Extend/c1Retract (extend/retract cylinder I), c2Extend/c2Retract (extend/retract cylinder II), vcExtend (extend cylinder III), vacuum_on/vacuum_off (turn suction unit on/off).

B. Technique usage example

In order to test our approach, we manually removed the Controller FB from the application, making the system control-free. First, we fixed the desired controller's interface, which included input events INIT and REQ, output events INITO and CNF, input variables M.O={c1Home, c1End, c2Home, c2End, vcHome, vcEnd, pp1, pp2, pp3, vac}, and output variables M.I={c1Extend, c1Retract, c2Extend, c2Retract, vcExtend, vacuum_on, vacuum_off}.

Second, we applied the developed scripts to generate the manual control HMI for output variables M.I (see Fig. 3) and to enable user and system behavior logging.

Third, we designed a set of nine test cases, where each one defines the order of work pieces the PnP manipulator has to process. For example, '1-2-3' is a scenario where first the manipulator is given piece number one, then piece number two, and, finally, piece number three. The nine test cases are as follows: '1', '1-2', '1-2-3', '2', '2-1', '2-3', '3', '3-2', '3-2-1'. Then the manual control HMI was used to execute these test cases, while execution scenarios were automatically recorded.

Fourth, we applied the proposed ECC construction algorithm to build an ECC consistent with recorded scenarios. The algorithm took less than a minute on a personal computer to complete. For comparison, the algorithm from [9] takes about 4.5 hours to find an ECC consistent with these scenarios. Finally, we added the constructed ECC to the original application and ran all the test cases to ensure that the ECC works correctly. The constructed ECC is shown in Fig. 6.

VI. Conclusion

In this paper we proposed an automated technique capable of inferring automata logic for MVC applications. The proposed approach has been implemented for IEC 61499 functions blocks. The feasibility of the approach has been demonstrated on the example of the PnP manipulator system.

One limitation of the presented approach is that the user bears all responsibility for the choices he makes during manual control of the system; handling unsafe or faulty choices of the user will be part of future work. Also, the approach can prove helpful only if performing manual control of the system is less difficult than designing the controller.

Acknowledgment

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