Discrete Control for Dependable IT Automation

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1 Introduction

Information technology (IT) administration is increasingly automated. Workflows—concurrent programs written in very-high-level languages—are an increasingly popular IT automation technology. Like multi-threaded programming, workflow programming is notoriously difficult and error prone. Concurrency, resource contention, race conditions, and similar issues lead to subtle bugs that can survive testing undetected. Static workflow analysis provides a reliable offline way to validate IT administrative actions before they are performed [2], complementary to dynamic validation and post-mortem root cause localization. Static analysis, however, merely detects defects; repair remains manual, time-consuming, error-prone, and costly. Manually-corrected workflows are less natural, less readable, and less efficient than the flawed originals.

This paper shows how *discrete control theory* can allow safe execution of unmodified flawed workflows by dynamically avoiding undesirable execution states, e.g., states that violate dependability requirements. By externally enforcing compliance with some dependability requirements, our approach allows programmers to write straightforward workflows instead of perfect ones; by partially decoupling workflow software from dependability requirements, it reduces the need to alter the former when the latter change. Classical control theory has recently been applied to several performance-related IT problems [1]. Discrete control employs very different methods and modeling formalisms [3] and is better suited to safety and dependability problems. Discrete control has been applied in domains ranging from manufacturing to telecommunications. However it has never before been implemented for any IT automation or CS systems problem.

2 Discrete Control Theory

Whereas classical control deals with continuous-state systems whose dynamics are described by differential equations, discrete control theory considers discrete-state systems with event-driven dynamics. Discrete control requires a model of the system to be controlled. We use a finite state automaton G representing all execution states reachable from the initial state, and we automatically generate G from a workflow. Undesirable behaviors are specified as sublanguages of the regular language associated with automaton G. A simpler mode of specification is to define *forbidden states* representing undesirable execution states. The goal of discrete control is to ensure that the system reaches satisfactory termination without entering forbidden states, even if worst-case sequences of uncontrollable state transitions occur. This goal is achieved in two stages: First, an *offline control synthesis* stage uses the system model G and the specification of terminal and forbidden states to automatically synthesize a discrete controller. Then during *online dynamic control* the controller selectively disables controllable transitions based on the current execution state.

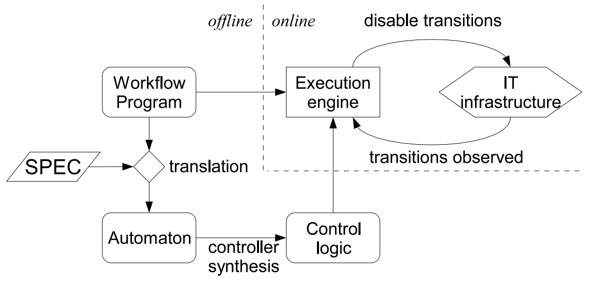

Figure 1: Workflow control architecture.

The synthesized controller should have two properties: First, it should be minimally restrictive, disabling transitions only when necessary to avoid forbidden states and livelock/deadlock. Second, it must not prevent successful termination. A controller with these properties restricts the system to its *maximally permissive controllable non-blocking sublanguage*, and existing methods can synthesize such a controller [3]. Control synthesis requires time quadratic in the size of G in the worst case. However, control synthesis is an offline operation; in the workflow domain, it does not increase execution time.

3 Discrete Control for Workflows

Figure 1 depicts our workflow control system architecture. We begin with a workflow consisting of atomic tasks organized via control-flow structures. Typical structures include sequence, iteration, AND-forks to spawn parallel executions, OR-forks to select a branch,

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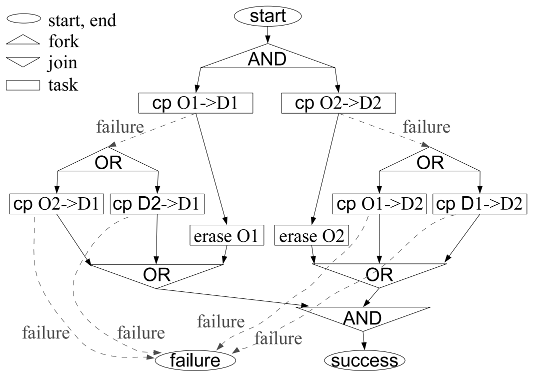
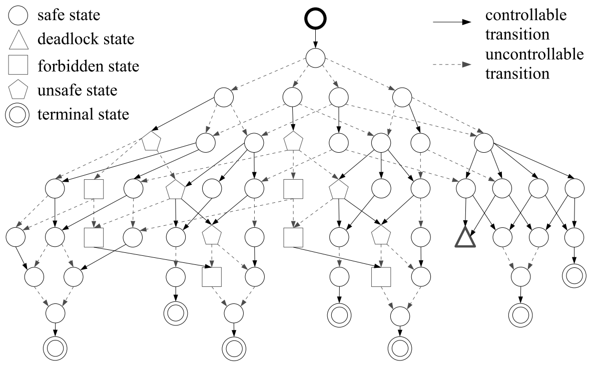


(a) Workflow diagram.



(b) State-space automaton for workflow of Figure 2(a). Deadlock state corresponds to double failure. Forbidden states contain neither two origin nor two destination copies. Unsafe states may reach forbidden states via sequences of uncontrollable transitions.

Figure 2: Data migration workflow

and AND/OR joins to "reconnect" flow after a fork. First, a translator converts the workflow into an automaton that models its control flow and reachable state space. Transitions in the automaton represent task invocation/completion, control structure entrance/exit, and resource acquisition/release; states represent the results of these transitions. The translator identifies uncontrollable transitions by high-level workflow features and can automatically detect livelock/deadlock states. The programmer may define additional application-specific forbidden states. Next, a discrete control synthesis algorithm uses the automaton to generate control logic that specifies which controllable transitions should be disabled as a function of current execution state. Both workflow→automaton translation and control synthesis are offline operations. At run time, the workflow execution engine tracks execution state and refrains from executing controllable transitions that the control logic disables in the current state. The result is that the system will avoid forbidden states whenever possible, regardless of uncontrollable transitions that may occur during execution.

Figure 2(a) shows a simplified data migration workflow that moves two original copies of a data set, O1 and O2, to destinations D1 and D2. The two branches of the AND-fork represent concurrent copy-erase operations. Uncontrollable "failure" transitions model the possibility that copy operations may fail. If the O1→D1 copy in the left branch fails, the workflow will retry from O2 or D2. However the workflow does not specify which; this decision is made by the execution engine. If the second attempt to create D1 also fails, the workflow will end in global failure. The right branch, responsible for creating D2, is symmetric. Tasks require exclusive access to copies of data.

The problem with this workflow is that if both O1→D1 and O2→D2 tasks fail, and if the response to these failures are attempts to copy D2→D1 and D1→D2 respectively, then the workflow deadlocks with each branch waiting for the other to complete. Static analysis alone can detect this problem, requiring a programmer to repair the flaw manually. Discrete control allows us to safely execute the flawed workflow without modification. The controller will avoid the deadlock state by disabling either D2→D1 or D1→D2 if both O1→D1 and O2→D2 fail. Figure 2(b) depicts the state-space automaton for our example workflow. There is one deadlock state corresponding to the above double failure.

Suppose a new requirement is imposed: At any instant in time, either both origin or both destination copies must exist. The workflow does not satisfy this new requirement because it may erase O1 before the O2→D2 copy completes. With discrete control, the new requirement can be satisfied simply by forbidding states that violate it and then synthesizing a new controller. The controller satisfies the new requirement by appropriately postponing erase operations. This scenario shows that discrete control can accommodate new requirements without modifying workflows.

In conclusion, we have described how discrete control methods can synthesize controllers from workflows and declarative specifications. These controllers add negligible run-time overhead, and they prevent undesirable behavior while otherwise restricting execution as little as possible. Extensive tests on real workflows bundled with Oracle BPEL Designer and on randomly-generated workflows demonstrate that offline control synthesis scales to workflows of practical size.

References

[1] J. L. Hellerstein, Y. Diao, S. Parekh, and D. M. Tilbury. *Feedback Control of Computing Systems*. Wiley, 2004.

[2] J. Mendling et al. A quantitative analysis of faulty EPCs in the SAP reference model. Technical Report BPM-06-08, Business Process Management Center, 2006.

[3] P. J. Ramadge and W. M. Wonham. Supervisory control of a class of discrete event processes. *SIAM J. Control Optim.*, 25(1):206–230, 1987.