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Model reverse-engineering of Mobile applications with exploration strategies ¹

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Abstract—This paper presents a model reverse-engineering approach, combined with automatic testing, for mobile applications that belong to the GUI application category. Our method covers the interfaces of an application to incrementally infer a formal model expressing the navigational paths and states of the application. The main contributions of this paper can be summarised as follows: we propose an original definition of the GUI application model which eases the limitation of the application exploration. Then, we propose an algorithm based upon the Ant Colony Optimisation technique which offers the possibility to parallelise the application exploration and to conceive any application exploration strategy as desired. Finally, our approach is experimented on Android applications and compared to other tools available in the literature.

Keywords-Model generation, Automatic testing, exploration strategies, STS, Android applications

I. INTRODUCTION

Many software engineering approaches rely upon models to automate some steps of development of an application. Unfortunately, these kind of approaches suffer from an indisputable problem which often make them impractical with many real world systems: writing models, especially exhaustive ones, is often a tedious and error-prone task. As a consequence, only partial models are often available which makes model-based approaches less interesting. For instance, Model-based testing is an approach which takes formal specifications to generate test cases, but the former have to be complete.

Model inference or model reverse-engineering is a recent research field that partially address this issue. Indeed, models can be inferred from application documentation or traces (sequences of actions given or observed from the application) for comprehension or to automatically carry out some tasks, e.g. the test case generation. Most of the model generation approaches, available in the literature, focus on GUI applications (a.k.a. event-driven applications), which offer a Graphical User Interface (GUI) to interact with and which respond to a sequence defined by the user. In short, these applications are explored (a.k.a. crawled) with automatic testing techniques for extracting traces to derive a model. Furthermore, a large part of the application defects

can eventually be detected during the process. Afterwards, these generated models may be manually extended, analysed with verification techniques or employed for generating test cases.

In this paper, we propose a model reverse-engineering approach, combined with automatic testing, which is dedicated to mobile applications. These GUI applications for smartphones, are usually poorly documented and are often manually tested. From a mobile application, our solution generates two STS (Symbolic Transition System) specifications, which can be seen as documentation either useful for maintaining the application or for comprehension, or for performing automatic analyses and generation (verification with existing tools, test cases, etc.).

Several works already deal with the crawling of GUI applications e.g., desktop applications [1], Web applications [2], [3], [4] or Mobile ones [5], [6], [7]. These approaches interact with applications in an attempt to either detect bugs or record a model or both. These previous works already propose interesting features, such as the test case generation from the inferred models. Nonetheless, it also emerges that many interesting issues still remain open. Firstly, experimenting the GUIs of Web or Mobile applications may lead to a large and potentially unlimited number of states that cannot be all explored. Furthermore, the application traversing is usually guided by one of these strategies: DFS (Depth First path Search) or BFS (Breadth First path Search). These are relevant on condition that all the application states would be explored. But when the GUI application state number is large or the processing time is limited, using other strategies could help in the exploration of the most interesting features of the application as a first step.

This paper presents an innovative model generation approach which overcomes the previous problems by putting forth the following features:

- model definition and compactness: we propose an original model definition specialised to GUI applications. Combined with our application exploration algorithm, this model especially offers the advantage to help limit the exploration and to prevent from a state space explosion. But, this model can still store the discovered interfaces and their properties instead of resorting abstract event-based descriptions only. These

¹Thanks to the Openium company for providing advice and comments on this paper and Android Applications.

detailed information are particularly relevant to later perform precise analyses. A bisimulation minimisation technique is also applied to yield a second reduced STS which can be more easily interpreted,

- test data generation: instead of using random test values, the values used to fulfil the application interfaces are constructed from several data sets, and in particular from a set of fake identities. Furthermore, the sets of test values are constructed by means of a Pairwise technique to reduce their size and the testing cost,
- strategy choice: the application exploration is here guided by strategies that are applied on the model under generation by means of the Ant Colony Optimisation (ACO) technique. We also show that our exploration algorithm, based upon the ACO heuristic, is highly parallelisable.

The paper is structured as follows: Section II sets down the terminology of mobile applications used throughout the paper and particularly presents our model definition. We present, in Section III, our mobile application exploration algorithm based upon the ACO heuristic. We give some experimental results and compare our approach with available tools in Section ???. We briefly present some related work and discuss about our proposal in Section V and we conclude in Section VI.

II. MOBILE APPLICATION MODELLING WITH STS

A. Terminology

We say that a mobile application displays (graphical user) interfaces, each representing one application state and the number of states being potentially infinite. An interface is generated by a component of the application. Here, we take back the notation used in the Android OS where such a component is called an *Activity*. These instantiate *Widgets* (buttons, text fields, etc.) and declare the available events that may be triggered by the user (click, swipe, etc.). A Widget is characterised by a set of properties (colour, text values, etc.); some of them are said *editable*, which means that their values can be provided by users at runtime.

We take as example the *Ebay Mobile* application, which is available on the *Google Play* store. Since this complex application owns 135 Activities, we only depict a part of its storyboard in Figure 1. The launcher interface is loaded by the first Activity *eBay* (interface 0). A user may choose to search form an item by clicking on the editable text field Widget. In this case, the Activity *MainSearchActivity* is reached (interface 1). For instance, if the user enters the keyword *shoes*, the search result list depicted in interface 2 is displayed; the Activity is unchanged. Then, three new Activities can be reached: 1) an Activity called *SegmentSearchResultActivity* (interface 3) displays a result when one element of the proposed list is chosen, 2) a *Scanner* Activity (interface 4) is started when the text field *Scan*

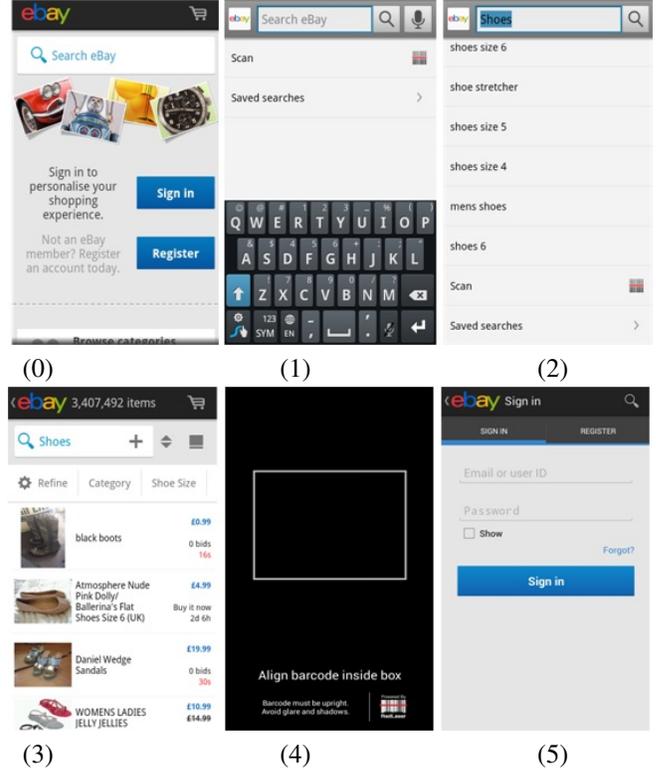


Figure 1: Ebay Mobile Storyboard

is clicked and a log-in process is performed on the when the saved search item is chosen (Activity *SignInActivity*, interface 4).

B. The STS model

To represent the behaviours of mobile application, we shall consider the Symbolic Transition System (STS) model, which is a kind of automata model extended with variables that encode the state of the system. Transitions also carry actions combined with parameters, guards and assignments. We chose the STS definition proposed in [8] which does not explicitly represent states in transitions. Instead, (*control*) *locations* are encoded with variables taking values in finite domains. This definition offers more flexibility to represent locations that have a precise meaning by means of variables.

Definition 1 (STS) A STS S is a tuple $\langle V, V_0, I, \Lambda, \rightarrow \rangle$, where:

- V is the finite set of internal variables and I is the finite set of parameter variables. A variable can have a simple type (Integer, String, etc.) or a complex type (List, etc.). We denote D_v the domain in which a variable v takes values. The internal variables are initialised with the initial condition $V_0 \subseteq D_V$, which is assumed to be unique,

- Λ is the finite set of symbolic actions $a(p)$, with $p = (p_1, \dots, p_k)$ a finite list of parameters in $I^k (k \in \mathbb{N})$. p is assumed unique,
- \rightarrow is the finite transition set. A transition $(a(p), G(p, v, T(v, p)), A(v, p, T(v, p)))$ is labelled by an action $a(p) \in \Lambda$. $G \subseteq D_p \times D_V \times D_{T(p \cup V)}$ is a guard on internal variables, parameters and $T(p \cup V)$ a set of functions that return boolean values only (a.k.a. predicates) over $p \cup V$. Internal variables are updated with the assignment function $A : D_V \times D_p \times D_{T(p \cup V)} \rightarrow D_V$ once the transition is fired.

Below, we adapt this generalised STS definition to express mobile application properties, i.e. interfaces and events.

C. Mobile application modelling with STSs

Usually, GUI application models show the available interfaces and the events that can be triggered. Some works [6], [9] proposed representing all the observed interfaces of a GUI application in a graph and to explore them all. Nonetheless, this solution is not the most appropriate in practice since the interface number may be potentially infinite. Other works [1] construct one state in a graph for every encountered Rendering component. We believe that this solution is too abstract since such a component may depict several different interfaces. Furthermore, the content of the interfaces, e.g., the text field values, is lost in the model but these data are usually considered as important for model analysis, test case generation, etc.

We have chosen to formalise a mix of these propositions with a specialised STS. Intuitively, as in the first previous solution, our model definition allows to stock the interfaces of a mobile application. Generally, a GUI application may produce a potentially infinite set of interfaces, but many of them are almost identical and only display different text field values. For a set of almost identical interfaces, we propose to only explore one interface in this set. To this end, we express an interface by the tuple (wp, wt) where wt is the list of Widget properties related to the text field values found in the interface and wp the remaining list of Widget properties. We define that a STS location is encoded by the variable loc , and captures a value list of the form (rc, wp, wt, end, ph) with rc an Activity name (or URI), accompanied by the Widget property lists wp and wt . Furthermore, these locations are completed with a boolean value denoted end indicating whether the application has to be explored from this location: when end is set to true, the exploration is stopped because an interface $(wp, wt2)$ almost identical to the current one (wp, wt) has been previously explored. Finally, the positive value ph denotes a pheromone amount that shall be used by apply the ACO technique. The purpose of this value is explained in the next Section.

We also interact with mobile applications by means of events, e.g., click, applied on Widgets. Furthermore, the

Widgets of an interface are eventually completed before triggering an event. We capture these events with STS transitions of the form $(event(widget), G, A)$. The guard G is composed of conjunctions which show the initial location of the transition, a constraint over editable Widgets expressing their completion with user values, and the value of $widget$, giving the Widget name on which is applied the event. The assignment A gives the final location of the transition.

It results that we express the functioning of a mobile application with the following STS model, called the STS Tree of an application:

Definition 2 A mobile application is modelled by the STS Tree $\langle V, V0, I, \Lambda, \rightarrow \rangle$ where:

- Λ gathers the available events of the form $event(widget)$,
- \rightarrow is composed of transitions $(event(widget), G, A)$ with a guard G of the form $[loc == (rc, wp, wt, end, ph) \wedge editable_constraint \wedge Widget == wn]$ and an assignment A of the form $loc := (rc2, wp2, wt2, end2, ph2)$:
 - the expression $loc == (rc, wp, wt, end, ph)$ gives the initial location of the transition, while the assignment $loc := (rc2, wp2, wt2, end2, ph2)$ gives the final location. rc is an Activity name, wt is a list of Widget properties relative to text field values, wp is a list of Widget properties excluding wt , end and ph are boolean values,
 - $editable_constraint$ is a conjunction of atomic expressions of the form $widgetprop == v$ with v a value and the variable $widgetprop$ corresponding to an editable Widget property.
 - $widget == wn$ denotes the Widget name on which is applied the event.
- $V0$ denotes the initialisation of the loc variable.

Figures 2, 3 and 4 illustrate an example of STS Tree derived from the Ebay Mobile Storyboard of Figure 1 with our approach. ****strategy????**** Due to lack of room and for readability, the locations are not detailed in the figure, but some of them are listed in Figure 4. The STS Tree is composed of several "click" actions applied on different Widgets (buttons, elements of listView Widgets, etc.). The actions are given in Figure 3. The location $loc0$ represents the initial interface of the application. $loc1$ is reached from $loc0$ by executing the action $a1$, i.e by clicking on the $home_search_text$ Widget. $loc1$ is composed of the Activity $MainSearchActivity$ which displays the editable $search_src_text$ Widget and several clickable Widgets (button, list, texts), for instance a button called $search_button$. The locations $loc6$ and $loc7$ are respectively reached after the completion of the $search_src_text$ Widget with the $All\ shoes$ and $shoes$ text values and the click on

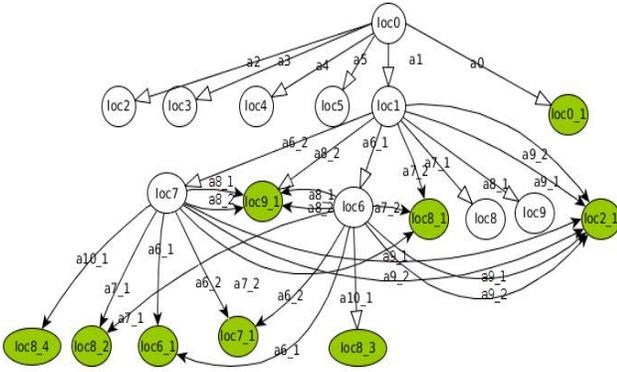


Figure 2: Ebay Mobile STS tree

Label	Action
a1	click(widget)[widget=id/home_search_text]
a6_1	click(widget)[widget=id/up ^ search_src_text=All shoes]
a6_2	click(widget)[widget=id/up ^ search_src_text=shoes]
a7_1	click(widget)[widget=id/search_button search_src_text=All shoes]
a7_2	click(widget)[widget=id/search_button search_src_text=shoes]
a8_1	click(widget)[widget=id/text1 ^ search_src_text=All shoes]
a8_2	click(widget)[widget=id/text1 ^ search_src_text=shoes]
a9_1	click(widget)[widget=id/text2 ^ search_src_text=All shoes]
a9_2	click(widget)[widget=id/text2 ^ search_src_text=shoes]
a10_i	click(widget)[widget=listElement at position i ^ search_src_text=shoes]

Figure 3: Actions and Guards of the STS Tree

the Widget *up* (actions *a6_1* or *a6_2*). These two locations corresponds to two different interfaces which differ from each other on the value of the *search_src_text* field and on the displayed item list number: one item is displayed for *loc6* and 10 for *loc7*.

The locations *loc8_j* that are reached from *loc6* or *loc7* with the actions *a10_i*, express *j* interfaces which only differ from the interface stored in *loc8* by some text field values. As a consequence, they are marked by end to stop the exploration.

After covering only 5% of the *Ebay Mobile* Activities, we already obtain 19 Locations in the STS Tree. This is why our approach, explained below, relies upon a minimisation technique to reduce this location number.

III. AUTOMATIC TESTING AND MODEL GENERATION WITH ACO

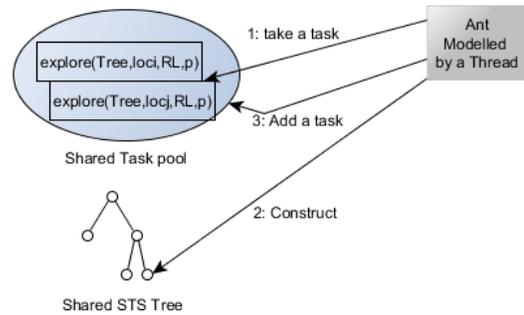
Intuitively, many inference model methods consists in analysing and completing interfaces with random test data and triggering events to discover new interfaces that are recursively explored in an in-depth manner. As a consequence, the application exploration is usually guided with either a DFS (Depth First path Search) or a BFS (Breadth First path Search) strategy. Nonetheless, when an application returns a high number of new interfaces, the graph to be explored

Loc	ActivityName	Widget properties		UE	env
		#list element	Edtxt0		
<i>loc6</i>	MainSearchActivity	1	All shoes	true	false
<i>loc6_1</i>	MainSearchActivity	1	All shoes	true	true
<i>loc7</i>	MainSearchActivity	10	shoes	true	false
<i>loc7_1</i>	MainSearchActivity	10	shoes	true	true

Figure 4: Locations definition

may become too large to visit in a reasonable time delay. The search is only performed to a limited depth, and the explored part of the application is not necessarily the most interesting one. In this section, we address this issue and we propose an algorithm which includes the possibility to define an exploration strategy.

Figure 5: Parallel exploration functioning



Our proposal applies strategies by means of the Ant Colony Optimisation (ACO) technique. With ACO, the optimal path search in a graph is performed by simulating the behaviour of ants seeking a path between their colony and a source of food: firstly the ants, explore randomly and lay down little by little pheromone trails that are finally followed by all the ants. In our case, this solution leads to the architecture illustrated in Figure 5. The STS construction is guided by laying down in locations an amount of pheromone with regards to the chosen strategy. Each location exploration is considered as a task that is placed into a task pool and executed by threads simulating ants. Then, our algorithm proceeds by exploring first the locations having the highest amount of pheromones. The process ends when the task pool is empty. These steps are explained below:

A. Application exploration

Algorithm 1 implements the initial part of this solution. It takes as input a GUI application *app* and starts it to analyse its first interface and to initialise the first location *loc0* of the STS Tree *Tree*. This step is carried out by one thread only. *** The analysis of an interface does not rise any technical difficulty with Android. Indeed, it is always possible to retrieve the Activity and the Widget properties of the current interface with testing tools such as Robotium ¹. Afterwards,

¹<https://code.google.com/p/robotium/>

Algorithm 1: GUI application exploration simplified Algorithm

```

input : Application app
output: STS Tree, MTree

// initialisation performed by one ant only
1 Start the application app;
2 Analyse the current interface -  $\zeta$  Activity rc, the Widget property lists wp, wt;
3 Initialise ph0 (depends of the chosen strategy);
4 loc0 := (rc, wp, wt, false, ph0);
5 Initialise STS Tree (VOTree = loc0);
6 Add (Explore(Tree, loc0, RL = {(rc, wp)}, p =  $\emptyset$ ) to the task pool;
// code performed by all the ants
7 while the task pool is not empty do
8   Take a task (Explore(Tree, loci, RL, p) having a location (rc, wp, wt, end, ph) with the highest pheromone amount ph;
9   Reset and Execute app by covering p;
10  Explore(Tree, loci, RL, p);
// code performed by one ant only
11 MTree := Minimise(Tree);
12 Me = Minimise(STS Extrapolation of Tree);

```

the interface exploration can begin: each thread (ant) executes the loop of Algorithm 1: while there is a task to do, an instance of the application is launched in a re-initialised test environment and a task (*Explore(Tree, loc_i, RL, p)*) having a location *loc_i*, composed of the highest pheromone amount, is picked out. This task aims at exploring one interface only and may produce other tasks. The set *RL*, used by *Explore*, stores the discovered locations in a reduced form (*rc*, *wp*). After the end of the exploration, a second STS *MTree* is computed with a minimisation technique.

The STS minimisation aims to yield a second STS, more compact in term of STS location number and more readable for application comprehension. Here, we have chosen a bisimulation minimisation technique since this one preserves the functional behaviours represented in the original model and reduces the location space without requiring to manually give a location set as proposed in [2]. The time complexity of this minimisation technique is also reasonable (proportional to $\mathcal{O}(m \log(n))$ with *m* the transition number and *n* the state number). A detailed algorithm can be found in [10]. This algorithm constructs the location sets (blocks) that are bisimilar equivalent. Due to lack of room, we only present in Figures 6 and 7, the minimised STS obtained from the STS Tree of Figure 2. Some locations are now grouped into blocks: for instance, the locations *loc6* and *loc7* are grouped onto the Block *B1* because the same action sequences leading to bisimilar locations can be executed from both *loc6* and *loc7*.

One task, pulled from the task pool, is now performed by calling the *Explore* procedure given in Algorithm 2. It takes the STS under construction *Tree*, a location *loc_i*, a path *p* and the set *RL* of discovered locations stored in a reduced

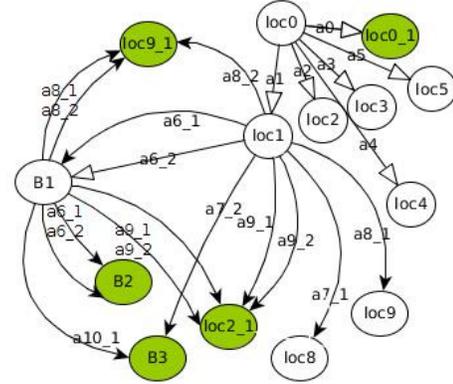


Figure 6: Minimised STS Tree

block	locations
B1	<i>loc6, loc7</i>
B2	<i>loc6_1, loc7_1</i>
B3	<i>loc8_1, loc8_2, loc8_3, loc8_4_i</i>

Figure 7: Location blocks of the minimised STS Tree

form. Initially, the procedure ends if a stopping condition, based upon the code coverage and on the processing time, holds. This condition allows to stop the exploration after a reasonable delay. Otherwise, the *Explore* procedure calls *GenConstraints* to analyse the current interface, extract the editable Widgets and to produce a set of constraints expressing how fulfilling these editable Widgets with test values. Similarly, the events that can be triggered on the Widgets are dynamically detected (with the Robotium tool). It results a set of couples (*event*, *w*) with *event* the event to apply on the Widget *w*. Then, the exploration of the current interface begins. Its editable Widgets are completed in accordance with a constraint *c*. A Widget *w* is stimulated with an event in reference to a couple (*event*, *w*) found in the Events set. This results in a new interface *Inew* (line 9). A *Ph_Deposit* procedure is called to compute the pheromone amount that shall be deposited in the arrival location of the transition constructed in the next step, with regards to the chosen strategy. The algorithm now checks whether this interface and its corresponding location have to be explored. Naturally, if *Inew* reflects the end of the application (exception, crash), *Inew* must not be explored. Furthermore, if *Inew* only differs from a previously encountered interface by its text field values, we also stop the exploration. This is done in the algorithm by checking if the list (*rc_j*, *wp_j*), extracted from *Inew* which excludes the Widget properties related to text field values, belongs to the set *RL*. If one of these conditions hold then a new transition carrying the arrival location (*rc_j*, *wp_j*, *wt_j*, *true*, *ph_j*) is added to the STS *Tree*. The boolean value *true* denotes that this location must not be explored. On the contrary,

Algorithm 2: Explore Procedure

```
1 Procedure Explore(Tree, loci, RL, p);
2 if [processing time  $\zeta T$  or code coverage  $\zeta CCJ$ ] then
3 stop;
4 Generate constraints with GenConstraints- $\zeta$  C;
5 Analyse the current interface  $\rightarrow$  Events;
6 foreach  $c \in C \wedge (event, w) \in Events$  do
7   fulfil the editable Widgets with c;
8   Apply event on the Widget w  $\rightarrow$  new interface Inew;
9   Analyse the interface Inew  $\rightarrow rc_j, wp_j, wt_j$ ;
10   $ph_j := Ph\_Deposit(loc_i, rc_j, wp_j, wt_j)$ ;
11  if Inew is empty or Inew reflects a crash or there exists
    ( $rc_j, wp_j$ )  $\in RL$  then
12    {Add a transition (event(widget),
       $G = [loc == loc_i \wedge c \wedge widget == w], A = (loc :=$ 
       $(rc_j, wp_j, wt_j, true, ph_j))$ )  $\rightarrow Tree$ ;
13    } (in critical section)
14  else
15     $loc_j := (rc_j, wp_j, wt_j, false, ph_j)$ ;
16    {Add a transition  $t = (event(widget), G = [loc ==$ 
       $loc_i \wedge c \wedge widget == w], A = (loc := loc_j))$   $\rightarrow Tree$ ;
17     $RL := RL \cup \{(rc_j, wp_j)\}$ 
18    Add the task (Explore(Tree, locj, RL, p.t)) to the task
    pool;
19    } (in critical section)
20  Backtrack(loci, p);
```

a new transition is added (with a location loc_j whose last boolean value is set to false). The arrival location loc_j must be explored. Therefore, a new task is added to the task pool (line 18).

To apply the next constraint and event, the application has to go back to its previous interface by undoing the previous interaction. This is done with the Backtrack procedure whose role is to undo the most recent action. When the direct interface restoration is not possible (when the backtrack mechanism is not implemented or when the application crashed), the Backtrack procedure resets the application and incrementally replays the actions of the path p .

This algorithm also relies upon the procedure *GenConstraints* to construct constraints expressing how to fulfil an interface under test with values. Due to lack of room, we present it succinctly. The *GenConstraints* procedure aims to generate constraints of the form $w_1.value = v_1 \wedge \dots \wedge w_n.value = v_n$, with (w_1, \dots, w_n) the list of editable Widgets of an interface and (v_1, \dots, v_n) , a list of test values. Instead of using random values like in many model inference approaches, we propose to use several data sets: a set *User* of values, eventually composed of logins and passwords, provided by a user, a set *RV* composed of values well known for detecting bugs, e.g., String values like "&", "", or null. A last set, denoted *Fakedata*, is composed of fake user identities. An identity is itself a list of parameters (p_1, \dots, p_m) , such as (name, age, email, address, gender), that are correlated together to form realistic identities. Both *User* and *RV* sets are segmented per type (String, Integer, etc.). We denote $type(User \cup RV) \subset User \cup RV$ the subset of

values having the type *type*. The *GenConstraints* procedure starts collecting the editable Widget list (w_1, \dots, w_n) . Every w_i is then associated to a specific data set as follows:

- 1) *GenConstraints* extracts the larger subset (w_1, \dots, w_k) which is also a subset of the parameter list (p_1, \dots, p_m) (we try to find a correlation between the Widget names and the identity parameters with regular expressions). This subset of Widgets is then associated to a list of "reduced" identities where the parameters which do not belong to (w_1, \dots, w_k) are removed. For instance, if two Widgets named *name* and *email* are found, the fake identities of *Fakedata* are parsed to remove the undesired parameters and to return the set of identities composed only of a name and an email,
- 2) each remaining Widget, is associated to the value set $t(User \cup RV)$ with t the type of data expected by the Widget (usually String). We obtain a list of value sets $\{V_1, \dots, V_n\}$ linked to the Widgets (w_1, \dots, w_n)

Now, instead of using a cartesian product to derive a set of tuple of values denoted V , we adopted a Pairwise technique [11]. Assuming that errors can be revealed by modifying pairs of variables, this technique strongly reduces the coverage of variable domains by constructing discrete combinations for pair of parameters only. Finally, the set of constraints C is derived from V .

Last but not least, our proposal also offers the advantage to be highly parallelisable. Indeed, the task pool is a known paradigm of parallel computing where the tasks of the pool are executed in parallel on condition that the tasks are independent. This is the case in our Algorithms since several application instances are experimented into independent test environments. All the threads share the same STS *Tree*, the same discovered location set *RL* and the same task pool implemented as an ordered list. This is why we added three critical sections in the Explore procedure to prevent concurrent accesses when transitions are added to the STS (line 12, 13), or when a task is added into the pool (line 18).

Complexity and termination of Algorithm 1: theoretically, this algorithm does not end if the number of new interfaces to visit is infinite. This is why we added a stopping condition in the Explore procedure. But, our algorithm only explores the interfaces which have new Widget properties (in excluding those related to text field values), and we have observed in practice that the number of these interfaces is often bounded. Consequently, our algorithm ends with most of the applications. Its complexity also depends on the chosen exploration strategy. Here, we assume that the latter aims at covering all the application interfaces. We also do not consider the number of threads. If we assume that the number of locations to visit is then bounded to n , Algorithm 1 has a complexity proportional to $\mathcal{O}(m+n+mn+2m \log(n))$ with m the number of transitions. For every location, the number of transitions m is finite and depends on the number

of events that can be triggered and on the number of test values used to fulfil the editable Widgets. More precisely, if an interface is experimented with e events and has k editable Widgets which have to be completed with nb values, then the number of transitions is equal to $m = n * e * nb^2$. The above algorithm complexity stems from the following steps: the Explore procedure covers every transition twice (one time to execute the event and one time to go back to the previous location) and every location is processed once. Hence, the complexity should be proportional to $O(m + n)$. But, sometimes the backtrack mechanism is not available. Hence, in the worst case, for every location, the application is reset and the path p , at worst composed of m transitions, is executed to reach each location. Furthermore, the minimisation procedure whose complexity is proportional to $\mathcal{O}(m \log(n))$, is called twice.

B. Exploration strategies

Different strategies can be now used to cover an application. We succinctly present some of them below. These have to be implemented in the *Ph_Deposit* procedure.

BFS strategy: this classical strategy can be expressed easily here. Whenever a new location is built, it is only needed to set the pheromone amount to 0. In our algorithm, a location being explored, is completely covered with the generated constraint set in a breadth-wise order first and each location is added to the end of the task pool (implemented as an ordered list). Thus, the newest discovered locations are not chosen immediately. As a consequence, the STS Tree is conceived in breadth-first order,

DFS-BFS strategy: a combination of both DFS and BFS strategies can be easily put into practice as follows: the location loc_0 is initialised with a pheromone amount equal to 0. Afterwards, whenever a new location is detected from an initial one loc , it is completed with the pheromone amount found in loc increased by 1. In this case, the next task chosen in the task pool shall be the one including the first discovered location from loc . Tacitly, a DFS strategy is followed. But, the current location being explored, is also completely covered in a breadth-wise order first,

Semantic-driven strategy: the number of observed crashes could also be considered in a strategy: when the number of crashes detected from the locations of a path p is higher than the number of crashes detected from the locations of another path p' , it may be more interesting to continue to cover the former for trying to detect the highest number of crashes. We call this strategy crash-driven exploration. This strategy can be conducted as follows: the pheromone amount is initialised to 0 in loc_0 . Whenever a new location loc_j is built, it is completed

with a pheromone amount equal to the addition of the pheromone amount found in the preceding location loc_i with the number of crashes (or exceptions) detected from loc_i ,

Semantic-driven strategy: these strategies denote an exploration guided by the recognition of the meaning of some Widget properties (text field values, etc.). Here, the pheromone deposit mainly depends on the number of recognised Widget properties and on their relevance. It is manifest that the semantic-driven strategy domain can be tremendously vast. For instance, for e-commerce applications, the login step and the term "buy" are usually important. Thereby, a strategy can be defined as: an authentication process is detected when a text field Widget has the type "passwdtype". In this case, the pheromone amount considered is set to X , otherwise it is equal to 1. When a Widget name is composed of the term "buy", the pheromone amount added in the location could be $Y < X$, etc.

Many other strategies could be defined in relation to the desired result in terms of model generation and test coverage. Other criteria, e.g., the number of Widgets, could also be taken into consideration. The strategies, succinctly described above, could also be mixed together.

The STS Tree of Figure 2 is constructed with Algorithm 1 and the DFS-BFS strategy as follows: the Explore procedure starts the exploration from loc_0 which holds a pheromone amount equal to 0. The actions a_0 to a_5 lead to new interfaces and locations loc_1, \dots, loc_5 that have to be explored. Here, the location loc_1 is chosen since it is the first new encountered location and has the highest pheromone amount. From loc_1 , the execution of actions leads to new locations: for instance the locations loc_8 and loc_{8_1} are reached with the actions a_{7_1} and a_{7_2} . These locations only differ by their text field values. Hence, the arrival location loc_{8_1} is not explored and marked by end. The next location having the highest pheromone amount is loc_6 . Therefore, this one is explored. And so on.

We also applied two different exploration strategies on the application "Ebay Mobile" to illustrate the different STS Trees which may be generated. With a DFS-BFS strategy, its interfaces were explored independently of their meaning. Figure 8 depicts a simplified graph, obtained with this strategy, showing that it started to examine the *RefineSearch* Activity. However, testing and exploring the account management part is usually considered as more important since defects may have a negative impact on user accounts. This choice can be followed with our approach by applying a semantics-driven strategy where the targeted Activities are those including Widgets of type "passwdtype" or Widget properties composed of the terms "account" or "sign in". Figure 9 illustrates the resulting graph after applying this strategy: here the Activity *SignAct*, allowing to manage user accounts, was directly targeted. This strategy makes the

generated STS more interesting to later analyse the security of the application or to generate security test cases.

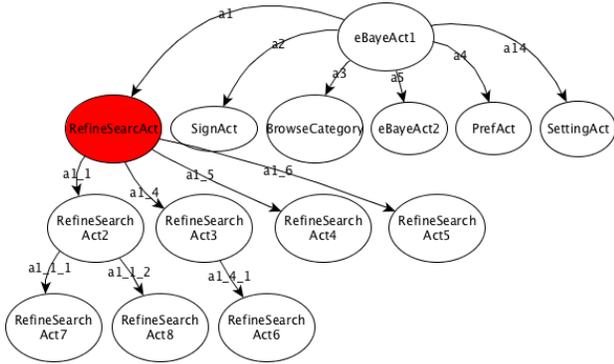


Figure 8: Ebay Mobile STS Tree obtained with a DFS-BFS strategy

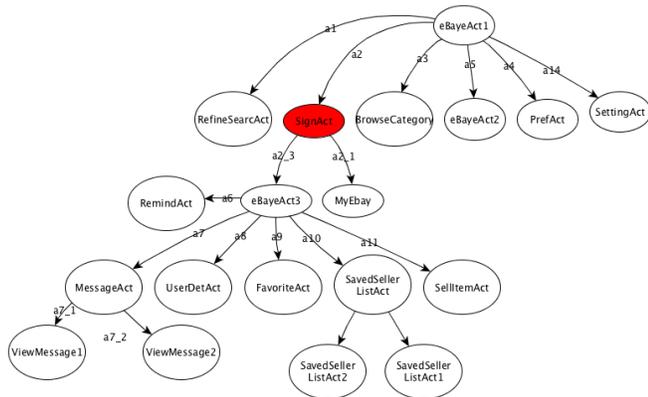


Figure 9: Ebay Mobile STS Tree obtained with a semantics strategy

IV. EXPERIMENTATIONS

We conducted several empirical studies to assess the overall results of our approach applied on Android mobile applications. Our prototype tool, called *MCrawlIT (Mobile Crawler Tool)*, is publicly available in a Github repository². It takes packaged Android applications (apk files) or source projects and stimulates them by calling the testing framework *Robotium*³. An application can be experimented in parallel by launching several Android emulators. We experimented our tool with a Mid 2011 computer including a CPU 2.1Ghz Core i5 and 4GB of RAM. We randomly chose some Android applications of the *Google Play* store and some applications taken as examples in other papers dealing with Android application automated testing for comparison purposes.

²<https://github.com/statops/apset.git>

³<https://code.google.com/p/robotium/>

Application	DFS(1)	DFS-BFS(1)	DFS-BFS(3)
Converter (1)	478	435	295
NotePad (2)	268	310	175
Tippy Tipper (3)	251	210	110
ToDoManager (4)	551	410	210
LotsA (5)	70	83	48
OpenManager (6)	696	560	489
HelloAUT (7)	106	216	201
TomDroid (8)	235	256	196
ContactManager(9)	233	216	135
OpenSudoku (10)	434	456	411

Figure 10: Processing time to explore all the locations with different strategies and number of simulators

Applications	Mon key	Orbit	GUI TAR	GUI Ripper	MCrawlIT	
					Code cov.	Act. cov.
NotePad (2)	60	82	-	-	88	100
ToDoManager(4)	71	75	71	-	81	100
HelloAUT (7)	71	86	51	-	96	100
TomDroid (8)	46	70	-	40	76	100
Youtube (11)	-	-	-	-	-	54.5
CNN (12)	-	-	-	-	-	73
TaskKiller (13)	-	-	-	-	-	57.1
Ebay (17)	-	-	-	-	-	19
WordPress (18)	-	-	-	39	-	47
CatLog (19)	-	-	-	-	77	80
DiskToFon (20)	-	-	-	-	42	67

Figure 11: Code and Activity coverage

Figure 10 presents the processing time for completely exploring these applications. The tool were applied with a DFS strategy (1 emulator), a mixed DFS-BFS (with 1 and 3 emulators in parallel). Our results firstly show that the chosen strategy has a direct impact on the processing time required to cover an application. In this experimentation, half of the applications are more rapidly covered with DFS-BFS traversing. For instance, with *ToDoManager*, using a DFS-BFS strategy instead of a DFS one, reduces the exploration delay by 140 seconds because all of its Activities are directly accessible from the initial one. These results depend mainly on the application structure though. When the insight of the application structure is known, our tool offers the advantage of choosing the most appropriate strategy. Otherwise, it may be chosen in regards to the purpose of the test. Figure 10 also shows that the parallelisation of our algorithm is effective. With three emulators, the processing time is always reduced. For instance, the parallel exploration of *Tippy Tipper* is achieved with a processing time almost divided by two.

Figure 11 shows the resulting code coverage obtained with our tool and other crawlers available in the literature: Monkey [12], Orbit [7], GUITAR [1], GUI Ripper [6]. With our tool, we provide the code coverage that is obtained for the applications whose source code is available (small open source applications). For the others, we can only give the Activity coverage which is the number of rendering components explored. Most of the other tools explore Android applications in an in-depth manner. Therefore, MCrawlIT

Applications	MCrawlerT	Monkey	GUI Ripper
Converter	9	4	
Notepad	2		
TomDroid	3	1	14
WordPress	51	3	37
CatLog	17	0	
DiskToFon	2	0	
Sipdroid	1	1	

Figure 12: Crash detection

was executed only with this strategy to carry out a fair comparison. These results show that the code coverage is between 42% and 96%. An application is incompletely covered either on account of unused code parts (libraries, packages, etc.) that are not called, or on account of functionalities difficult to start automatically. The code coverage achieved with MCrawlerT is either equivalent or higher than the one given by the other tools. For instance with *TomDroid*, we obtained 76 %, whereas ORBIT covers 70%, Monkey 46% and GUI Ripper 40% of the code. ORBIT offers a better code coverage with *Contactmanager* though. Indeed, users interact on this application with long click events that are supported by Orbit but not yet by our tool. The last lines of Figure 11 show the results obtained with larger applications (*Youtube* to *DiskToFon*). Since the time required to discover these applications may be long, we have limited the exploration time to 30 minutes. Without limitation, the coverage should strongly augment. Surprisingly, this kind of application is not considered by the other tools.

Finally, Figure 12 illustrates the number of observed crashes while exploring some Android applications with our tool *MCrawlerT*. We also compare these results to those obtained with the tools *Monkey* [12] and *GUI Ripper*. The processing time was limited to 30 minutes for the two first tools. For GUI Ripper, we have taken back the experimental results given in [6] that were obtained with a processing time varying between 3 and 5 hours.

MCrawlerT outperforms *Monkey* in automatic crash detection, which is not surprising since it covers deeper Android applications. The comparison with GUI Ripper is less obvious since the authors only provides two results for this tool. For the *WordPress* application, *MCrawlerT* detects more crashes than *GUI Ripper*, and on the contrary, more crashes are detected with *CatLog*. But the time processing of GUI Ripper is twelve times more long.

All these experimental results on real applications tend to show that our tool is effective and leads to substantial improvement in the automatic testing and model inference of GUI applications.

V. RELATED WORK AND DISCUSSION

Several papers dealing with automatic testing and model generation approaches were issued in the last decade. Here, we present some of them relative to our work:

Firstly, Several works were proposed for white-box systems [5], [3]. For example, Contest [5] is a testing framework which exercises smartphone applications with the generation of input events. This approach relies upon a systematic test generation technique, a.k.a. concolic testing, to explore symbolic execution paths of the application. These white-box based approaches should theoretically offer a better code coverage than the automatic testing of black-box systems. However, the number of paths being explored concretely limits to short paths only. Furthermore, the constraints have not to be too complex for being solved. As a consequence, the code coverage of these approaches may be lower in practice.

On the other hand, many black-box based methods were also proposed. Memon et al. [1] initially presented GUITAR, a tool for scanning desktop applications. This tool produces event flow graphs and trees showing the GUI execution behaviours. Only the click event can be applied and GUITAR produces many false event sequences which may need to be weeded out later. Furthermore, the actions provided in the generated models are quite simple (no parameters). Mesbah et al. [2] proposed the tool Crawljax specialised in Ajax applications. It produces a state machine model to capture the changes of DOM structures of the HTML documents by means of events (click, mouseover, etc.). An interesting feature of Crawljax is the concatenation of identical states in the model under construction, by comparison based on the DOM structure. This helps reduce the number of states which may be as large as the DOM modifications. In practice, to limit the state space and to avoid a state explosion problem, state abstractions should be given manually to extract a model with a manageable size. The concatenation of identical states proposed in [2] is done in our work by minimisation. Although this minimisation guarantees to keep the original functional behaviour of the model, the concatenation in [2] requires less time computation and sounds to provide good results.

Since our experimentation is based on Android applications, we explore more cautiously this field in the following. Google’s Monkey [12] is a random testing tool (events and data) offering light coverage especially when an authentication is required in the application. No model is provided. Amalfitano et al. [6] proposed GUI Ripper, a crawler for crash testing and for regression test case generation. A simple model called GUI tree depicts the observed GUI. Then, paths of the tree not terminated by a crash detection, are used to re-generate regression test cases. Joorabch et al. [9] proposed another crawler, similar to GUI Ripper, dedicated to iOS applications. As previously, a tree is constructed by a depth-first path search algorithm. A tree state is composed of the current GUI and of the properties of the GUI. These help to easier recognise application states. In comparison to these works, our generated models are much more detailed and can be used to derive new test cases with

less efforts since all the actions and parameters can directly be found in the model. We also consider several exploration strategies. The novelty of the work proposed by Yang et al. [7] lies in the static analysis of the Android application code to infer the events that can be applied to the GUI. The graph of the application, expressing the calling methods, is initially computed and filtered out to list the *listener* methods and events. Then, a classical crawling technique is employed to derive a tree composed of events. This grey-box testing approach was implemented in the Orbit tool. When only one emulator is used, this approach should cover an application quicker than our proposal since the events to trigger are listed by the static analysis whereas we try to detect them dynamically or we try all the possible events when this detection is not possible. But Orbit can be applied only when the application source code is available. This is not the case for many Android applications. Furthermore, our tool should cover an application quicker than Orbit since the former can be experimented in parallel with several emulators. Another strong advantage proposed in our approach, is the support of different exploration strategies. These can reduce the exploration time when the application structure is known or can guide the exploration when the application interface number is large. Our generated models are richer and are more compact thanks to the minimisation process.

VI. CONCLUSION

This paper presents a formal model inference approach for Mobile applications, which performs automatic testing through application interfaces and which explores applications by means of strategies. For one application, two STS models are generated by this approach. Both express the functional behaviours of the application, but the second one is reduced with a bisimulation technique for readability.

In comparison to the application crawlers available in the literature, this approach takes another direction by proposing two following main contributions. We propose a formal model definition whose aims are to store rich details about the encountered interfaces and to help reduce the application exploration. Our algorithms are based upon the application of the ACO technique to guide the application exploration with strategies that can be modified by managing differently the pheromone deposit in locations.

Our experimental results show that this approach can be used in practice: the prototype tool provides a good application code coverage in a reasonable time delay. Furthermore, the generated models are compact and can be reused for automatic test case generation since the STS Tree model stores all the properties of the explored interfaces.

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