Comparison and Analysis Between Automatic Exploration Tools for Android Applications

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Abstract

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The amount of android applications is having a tremendous increasing trend, leading the mobile software market to exert pressure over practitioners and researchers about several topics like application quality, frequent releases, and quick fixing of bugs. Because of this, mobile app development process requires of improving the release cycles. Therefore, the automation of software engineering tasks has become a top research topic. As a result of this research interest, several automated approaches have been proposed to support software engineering tasks. However, most of those approaches that provide comprehensive results use source code as entry, which due to privacy factors imposes hard constraints on the implementation of those approaches by third-party services. Nevertheless, the market is leading practitioners to crowdsource/outsource software engineering tasks to third-parties that provide on-the-cloud infrastructures.

Solutions that rely on third-party services cannot use state-of-the-art automated software engineering approaches because practitioners only provide them with APK files. Therefore, approaches that work at APK level (i.e., do not require source code) are desirable to enable automated outsourced software engineering tasks. As an initial point, in this thesis we explore the possibility of performing automated software engineering tasks with APKs, and in particular we use mutation testing as a representative example. Our experiments show that mutation testing at APK level outperforms (in terms of time and amount of generates mutants) the same task when conducted at source code level.

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Chapter 1

Introduction

Parafrasear lo que dice aquí, decir que este gran número de aplicaciones por fortuna a llevado a un gran número de estudios para mejorar la cobertura de código que se logra durante las pruebas automáticas, y también cubir diferentes estados del celular como modo avión con carga sin carga y demás, dada la gran cantidad de herramientas, los desarrolladores pueden sentirse sobrecargados, pueden exitir muchas opciones y pueden que no se elija la mejor herramienta. Los desarrolladores necesitan formas de elegir la mejor herramienta que se adapte lo mejor posible a sus necesidades.

Mobile markets have pushed and promoted the raising of an interesting phenomenon that has permeated not only developers culture, but also human beings' daily life activities. Mobile devices, apps, and services are helping companies and organizations to make "digital transformation" possible through services and capabilities that are offered ubiquitously and closer to the users. Nowadays, mobile apps and devices are the most common way for accessing those services and capabilities; in addition, apps and devices are indispensable tools for allowing humans to have in their phones, computational capabilities that make life better and easier.

The mobile apps phenomenon has also changed drastically the way how practitioners design, code, and test apps. Mobile developers and testers face critical challenges on their daily life activities such as (i) continuous pressure from the market for frequent releases of high quality apps, (ii) platform fragmentation at device and OS levels, (iii) rapid platform/library evolution and API instability, and (iv) an evolving market with millions of apps available for being downloaded by ends users [**joorabchi2013real**, **palomba2018crowdsourcing**]. Tight release

schedules, limited developer and hardware resources, and cross-platform delivery of apps, are common scenarios when developing mobile apps [**joorabchi2013real**]. Therefore, reducing the time and effort devoted to software engineering tasks while producing high quality mobile software is a "precious" goal.

Both practitioners and researchers, have contributed to achieve that goal, by proposing approaches, mechanisms, best practices, and tools that make the development process more agile. For instance, cross-platform languages and frameworks (e.g., Flutter, Ionic, Xamarin, React Native) contribute to reducing the development time by providing developers with a mechanism for building Android and iOS versions of apps in a write-one-run-anywhere way [**joorabchi2013real**, **fazzini2017automated**]. Automated testing approaches help testers to increase the apps' quality and reduce the detection/reporting time [**choudhary2015automated**, **kochhar2015understanding**, **linares2017continuous**]. Automated categorization of reviews also helps developers to select relevant information, issues, features and sentiments, from large volume of review that are posted by users [**palomba2018crowdsourcin**
villarroel2016release, **di2016would**]. Moreover, approaches for static analysis, are helping developers to early detect different types of bugs and issues that without the automated support could be time consuming for developers — when doing the analysis manually [**li:IST2017**]. Both static and dynamic analyses have been used with the aforementioned approaches, with a special preference for static analysis on source code.

The developers community is quickly moving towards using cloud-services and crowd-sourced services for software engineering tasks [**Leicht2017IEEESoftware**, **stol2017crowdsourcing**]; using those services is becoming a common practice of mobile developers who want to reduce costs and the time devoted for an activity. For example, the Firebase Test Lab platform [**firebase**] provides automated testing services, in particular, it automatically executes/explores a given app (provided by the developer as an Android APK file), and reports crashes found on a devices matrix that is selected by the user. However, the lack of knowledge of source code internals imposes a limitation on the usefulness and completeness of the results reported back to the users.

1.1 Problem Statement

// TODO explicar el problema que se quiere solucionar. Para mi es el comparar las diferentes herramientas puede tomar tiempo y elegir la correcta para un proyecto o para una aplicación puede tomar tiempo valioso

1.2 Thesis Goals

The main objective of this thesis, is to provide quantitative and qualitative information of the most widely used automatic exploration tools, to facilitate developers in the selection of the right tool that suits their needs. Under those circumstances, the next specific objectives were proposed.

1. Compare the tools by their exploration coverage
2. Compare the tools by the number of unique error traces discovered while exploring an application.
3. Compare the tools using qualitative aspects such as, is the tool a open source project? Is the tool free? Is the tool allowing introduce login values? how useful is the tool report for developer to reproduce, find and fix bugs?

1.3 Thesis contribution

The main contribution of this thesis is to provide developers with enough information to decide which is the best automatic exploration tool for their projects.

1.4 Document Structure

Chapter 2

Related work

2.1 Static Analysis of Android Packages

// TODO Agregar la sección por cada related work

Chapter 3

Solution Design

3.1 General Approach

As expected, para cumplir con el objetivo general de esta tesis se deben cumplir con los objetivos especificos, una vez estos sean completados a cabalidad entonces se tiene el objetivos general completado. La idea es que estos objetivos especificos lleven o ayuden a llegar al cumplimiento de este objetivo general. Se debe explicar cómo se cumplió con cada uno de ellos y al final explicar cómo se llegó a cumplir con el objetivo general

Explicar la creación de las otras 2 herramientas y cómo se usaron, para qué fueron creadas y cómo es la idea detrás de ellas.

With the purpose of enabling the execution of software engineering tasks at APK level, we propose a three phase process depicted in Figure **??**. The first phase consists of APK processing in order to generate models of the application, and the second phase consists of using those models by a certain module that represent a software engineering task desired by users. The final phase consists in rebuilding the APK when required, as in the case of mutation testing or app instrumentation for dynamic analysis. Note that enabling automated software engineering tasks at APK level is our long term goal, therefore, rebuilding the APK (but whitout decompiling the app to get the source code) is a required step in our approach.

APK processing. The first step during the model generation is decoding an APK file to be able to extract the Android opcodes and resources. Note that an APK is a zip file that contains resources files and a classes file that include the opcodes in DEX format for all the classes belonging to an Android app (including libraries). Based on the wide usage of SMALI as intermediate representation (top 2 according to Li *et. al.,* [**li:IST2017**]) and that it keeps about 97% of the information in an APK [**arnatovich2014empirical**, **arnatovich2018comparison**], we propose it

as the representation used for the models extraction. There are already parsers and lexers for SMALI which allows the extraction of abstract syntax trees (ASTs). Concerning the textual information available in resources files, it can be easily extracted because of the XML nature of those files in Android. Note that extracting SMALI code does not require de-compilation to original source code (*e.g.,* Java) which is time consuming and prone to de-compilation errors.

Software Engineering Tasks modules. Because SMALI can be used to extract representations and models such as ASTs, control flow graphs, among others, a plethora of analysis can be instantiated and without the need of original source code. Given the models of the application, implementing a software engineering task must be done on a separate module. These modules must be able to consume the models and provide a comprehensive result to the user. For example, a mutation testing module at APK level must use the AST models extracted from SMALI code to (i) identify the possible mutable snippets of code, and (ii) mutate the original app.

Re-building/packaging the app. The last phase of this process, consist of going back from decoded SMALI representation to an executable APK file, which does not require recompiling the modified code. However, note that this requires to be very careful when modifying the SMALI code to avoid injecting bugs into the app when the SMALI syntax is not properly used.This building process must be called by each software engineering task module, making sure all modules that require the execution of this process use the same format to deliver the internal result.

3.2 MutAPK

In order to validate the feasibility of our proposed approach we decided to implement it using mutation testing as a reference. As it was shown in the Section 3, mutation testing is still one of the software engineering tasks that has not been developed at APK level. Consequently, we implemented the proposed approach in a tool (***MutAPK***) that allowed us to compare the obtained results when working in the scenarios of having source code, and having only APK files.

As it was mention before, MutAPK must comply to some must-have rules for all mutation testing tools, it has a set of mutant operators, it provides the possibility to select the mutant operators that will be executed, it defines in detail the short process required for its extension and enables parallel execution. MutAPK is an Open Source project available at https://github.com/TheSoftwareDesignLab/

MutAPK. In the following sections, we describe MutAPK according to its workflow described in Figure **??**

3.2.1 APK Processing

Unpackaging/Packaging APK

Recalling the study by Arnatovich *et al.* [**arnatovich2018comparison**], we use APKTool, which allows us to process an APK returning a folder with all the resource files decoded and the source files disassembled into SMALI files. Additionally, code-related files are presented in a useful project like file structure. Because of this, some source code analysis tasks that are based in file location can be easily translated to be executed over APKTool decoding result. At the same time, APKTool allows to build an unsigned apk from the previously mention files. Therefore, an application can be modified in its SMALI representation and then packaged again into an APK for its use.

Derivation of the Potential Fault Profile

We followed the same approach proposed by Linares-Vásquez *et al.* [**linares2017enabling**, **Moran:ICSE18**] Therefore, we detect mutation locations by extracting a Potential Fault Profile, and then we implement mutation operations on those locations. The ***P**otential **F**ault **P**rofile **PFP*** is a set of code locations that represent potential points were a fault can be injected. These potential fault injection points are defined through the mutation operators shown in the Section 3.2.2. For the implementation of MutAPK, the PFP definition was inherited from MDroid+. First, both XML and SMALI files are statically analyzed searching for instructions that comply with the characteristics defined in the mutation operators. This previous process, also inherited from MDroid+, consist for XML files of going through the content looking for matches between the file tags and the different mutation operators potential fault injection points.

On the other hand, for SMALI files the process is based on the Abstract Syntax Tree that is obtained using the lexer and parser created by APKTool to perform the disassembling of an APK. In particular, MutAPK uses the visitor design pattern to identify the possible locations. Knowing this, the process can easily be extended to add new operators and to provide more comprehensive analysis of the app (*i.e.,* resource and SMALI files) if needed. The final result of the PFP derivation process is a list that joins the potential fault injection points with the mutation operators that can be applied to those locations.

3.2.2 Mutation Testing Module

Operators

We built upon the 38 operators proposed by Linares-Vásquez *et al.* [**linares2017enabling**, **Moran:ICSE18**] , which are representative of potential fault in Android apps and can be found either on source code statements, XML tags, or locations in other resource files. In MutAPK we implemented (i) the 33 operators implemented in MDroid+ that do not lead to compilation errors, and (ii) two additional operators not available in MDroid+.

Therefore, our work was to translate the operators implementation from the original source code-based implementations to the corresponding implementations in the SMALI representation. In order to do this, we manually selected 11 apps that had potential locations for implementing the operators. Given those applications, we built the APKs using Android Studio and disassembled manually each one to recognize the direct translation of each mutation original statement. After this dictionary is created, we proceeded to mutate manually the source code of these 11 applications and proceed to generate again the APK files. Finally we performed a diff comparison between the SMALI representation of the original version against the SMALI representation of the mutated version. Because of this, we were able to translate successfully each mutation operator from source code to SMALI representation. With this procedure we derived the list of operators implementation at APK level; the details of each operator are available in our online appendix [**MutAPK**].

Mutant Creation

We start by unpackaging the apk into a temporal folder. After that, the PFP is derived and a list of potential fault injection locations is created. We now can use the defined mutation rules to generate the mutants, however, in order to make this process as efficiently as possible, MutAPK provides the option to parallelize the mutant creation. For each location in the PFP, a copy of the disassembled apk is created. After the copying ends, based on the mutation operator associated, a new process that translate the mutation rule into an actual change is executed over the exact location inside the associated folder. Next, a compilation process is triggered in order to generate as result an APK. As it was said before, this process can be parallelized and each task consist of: copying the dissambled apk, mutating either a resource file or a SMALI file, and finally compiling the result to

obtain an APK. Nota that while MDroid+ only generates the source code of the mutants, MutAPK is able to generate APKs ready to install and test.

Extensibility

Due to the fast change of the android framework, MutAPK must provide the possibility to add new mutation operators easily. Therefore, in order to enable a new mutation operator some changes must be implemented: (i) create a new detector/locator that is capable of finding the correct position that provides all the information needed to create a *Mutation Location* defined in MutAPK; (ii) a mutator, that is capable of using the previously identified location information to mutate the code or resource file; (iii) update the *operator-types.properties* file found under the "src/uniandes/tsdl/mutapk" folder to add the new mutation operator file path with its defined id; (iv) modify *OperatorBundle.java* (in case the new operator is text-based) to add the new text detector and (v) update the *operators.properties* file.

At the same time, MutAPK counts with an *extra* folder where the external libraries are located. Therefore, if user wants to improve the file analysis process or wants to execute a more specialized process over the application, he can save the library files in this folder and manage them easily. MutAPK has in this *extra* folder the *jar* file provided by APKTool. Note that here there is a big difference with MDroid+ implementation; because in MDroid+ the source code must be compiled, then it requires in the extra folder all the libraries required to compile the source, code. This is not required in MutAPK because we are already working with "compiled" code.

3.2.3 Tool Usage

MutAPK has been designed to work as a command line tool. In order to use it, the user must have installed Maven and Java. The MutAPK repository[**MutAPK**] must be cloned and then packaged using the following commands

LISTING 3.1: Git and Maven commands to build MutAPK

```
git clone https://github.com/TheSoftwareDesignLab/MutAPK.git
mvn clean
mvn package
```

After that, the jar file called MutAPK-<version>.jar will be located in the *target* folder. That file can be relocated and used in other places.

When the command is executed in the console , the selected operators and the amount of mutants that are going to be generated for each operator (Listing **??**) are logged. Additionally, when all mutants are generated a log of the mutation process can be found at the Output Folder defined in the command. This log allows testers to identify what was the mutation applied on each mutant.

As an extension, for testing purposes MutAPK creates 2 csv files: (i) mutants that were successfully compiled, and (ii) summary of the time consumed to mutate and to compile each mutant. It is worth noting that even if the mutant do not compile correctly the second file register the time it took the compilation to fail.

Chapter 4

Empirical Study

4.1 Study Design

Comenzar con los objetivos de la tesis. Explicar por qué se seleccionaron las herramientas (RIP, TestLab, etc) Explicar las apps utilizadas en el estudio. explicar el workflow de cómo se obtuvieron los resultados. mostrar los resultados y analizarlos.

In order to measure the method coverage reached by an exploration tool in one application, there is the need to know how many methods there are in the application and how many methods were called during the exploration. To achieve that, the application developers could count the number of methods in their project and write log lines at the beginning of every method. After that, they will need to compile, run the exploration tool against their application, measure the number of methods that were called during the exploration and compute statistics.

With that in mind, this study consists of nearly the same stages, i. instrumentation, ii. exploration, iii. coverage analysis, iv. summarize, and v. compute statistics. The stages ii. and iii. were repeated 10 times for every application that was selected, that leaded to the iv. stage.

The different stages were completed as follow:

Stage i: The applications' instrumentation was made by using InstruAPK. It is an instrumentation tool developed mainly for this study. This tool uses APKTool, a known Java application that allows inverse engineering in Android apps, allowing applications' instrumentation without the need of recompiling their source code. APKTool decodes the apk and the result is the smali representation of the app source code, These smali files are analysed in order to find all the methods to be instrumented and then, the log code is injected at the very beginning of

each method. Its important to notice that no external libraries methods are instrumented. InstruAPK only search for methods following the android project structure that uses the application package name to store the application source code.

Stage ii: The exploration was made by four different automatic exploration tools. two from the industry and two from the academic side. The first tool was Firebase Test Lab. it was selected for being widely used in industry and for also being a Google product. The second one, Monkey, was selected for being the most basic one and because it is also included in the SDK for developing Android Apps. The third one, Droidbot, was selected from the academic side. Droidbot has been a point of study for many researches. Many others tools have based their functionality on this tool. The last one is RIP, this tool was selected for being of special interest for us. It is our own exploration tool and is is currently an active project inside the Software Design Lab at University of Los Andes.

Every tool was executed ten times per application, and every execution with a maximum time of 30 minutes. Some tools ended its exploration before the max time. The number of executions and the maximum time were arbitrary decisions that were made because of time limitations for the study. Although, during the study was notice that most of the tools ended the exploration or reached their maximum coverage within the first 15 minutes. Which means that the maximum time for exploration was more than enough in almost all cases.

stage iii: The coverage measurement was made by CoverageAnalyzer. It is a Java Application created mainly for this study. This tool analyses the resulting logcat of an Android phone, when executing an application that was instrumented by InstruAPK. It extracts different data such as, number of methods called, number of methods never called, number of error traces of the application being analysed, most called methods, less called methods, as well as the time stamp of all calls of every method. It is important to notice that the possibility of extracting all those information is because InstruAPK provides it.

stage iv: Due to the multiple executions of every APK per tool, it is important to summarize de data. The final report contains the total number of unique methods called during all ten executions, reporting only the first time they were called. The exploration reports are analysed and filtered as well.

stage v: This is the final stage of the study that involves, understanding data, computing statistics, creating graphs, extract insights and conclusions.

TABLE 4.1: Applications used for the study

App ID	Package Name	# Methods Reported by APKAnalyzer	# Methods Instrumented by InstruAPK
1	appinventor.ai_nels0n0s0ri0.MiRutina	61993	9351
2	com.evancharlton.mileage	4000	1162
3	com.fsck.k9	18799	7003
4	com.ichi2.anki	32370	2209
5	com.workingagenda.devinettes	19274	66
6	de.vanitasvitae.enigmandroid	13083	574
7	info.guardianproject.ripple	19429	100
8	org.connectbot	20606	1145
9	org.gnucash.android	75473	504
10	org.libreoffice.impressremote	14691	649
11	org.lumicall.android	45784	540

Besides that, for this study, a set of 11 applications was used. This set is a subset of a set of open source applications utilised inside The Software Design Lab research group for other studies and tests, including RIP. Every APK in the subset should be successfully instrumented by InstruAPK, it should compile without any problem after instrumentation and it should be launch in an emulator without any issue after instrumentation.

4.2 Context of the Study

In order to present a fair comparison between MutAPK and MDroid+, we have used the same apps MDroid+ used for their experiments. This 54 applications presented in Table 4.1 belong to 16 different categories of the Google Play Store. It is worth noticing that these 54 applications are open source and allows us to study the way code statements are translated from JAVA to SMALI.

In order to collect data that allow us to answer the research question, we compared MutAPK to an existing tool for mutation testing that works at source code level (MDroid+ **[linares2017enabling]**). The experiments were executed on a class-server machine. Note that in MutAPK, we implemented only 35 of 38 operators listed in Table **??** because the other 3 operators lead to non-compilable results. In order to analyze the impact of mutant generation process in MutAPK, we collect: (i) number of mutants generated per mutation operator per application; (ii) number of mutants that compile after mutation; (iii) mutant generation time (*i.e.,* the time required to generate each mutant) and (iv) mutant building times (*i.e.,* the time required to compile each APK file)

4.3 Results: Impact of generating mutants at APK level

$RQ_{1.1}$: To study our results, we present them in two stages, first we show a comparison where only the 33 mutants in both MDroid+ and MutAPK are taken into account. In Figure **??** we show the total amount of generated mutants per app.

MutAPK generates around 30 more mutants per app (17% more than MDroid+). However, if all operators are taken into account, the difference between the amount of mutants get bigger. Figure **??** shows the amount of generated mutants per app. As it can be seen, MutAPK outperforms MDroid+ generating in average 1211 more mutants per app, this corresponds to 7.3 times more mutants. For further analysis of the results at app level, we added the Tables **??** and **??**, where all info collected is summarized around apps (See Appendix A). Also, we show in Figure **??** that the amount of mutants generated per mutant operator are very similar between MutAPK and MDroid+. It is worth nothing that this figure does not take into account the 63441 mutants generated by one of the operators implemented only in MutAPK.

$RQ_{1.2}$: If we consider again only the 33 shared mutants, in Figure **??** we can see that MutAPK generates around 16% of non-compilable mutants while MDroid+ generates only 0.5%. Nevertheless, when using all operators MutAPK generates around 2.36% of non-compilable mutants while MDroid+ lightly increase its rate to 0.6%. At the same time, Figure **??** shows the percentage of non-compilable mutants in terms of the mutant operators, from this we can see that there is also a similar behavior for both. Specifically, MutAPK generates in average 0.1% non-compilable mutants while MDroid generates 0.05%.

$RQ_{1.3}$: The most important result is the execution time. MutAPK takes only 3% of the time (144,66ms) required by MDroid+ (4,6 seconds) to mutate a copy of the app. Therefore, due to the infraestructure used to run our study, MutAPK takes 9 seconds to generate all mutants for an app (on average), while MDroid takes 19 seconds.

$RQ_{1.4}$: For compilation, MutAPK spends only 6.3% of the time required by MDroid+ to compile a mutant. Consequently, MutAPK takes 11 min to compile all mutants for an app (on average) while MDroid+ takes 13 min.

Finally, if all mutant operators are selected, MutAPK takes around 9.63 hours to complete the mutation and compilation process for the 54 apps while MDroid+ takes 12 hours. It is worth remembering that MutAPK generates around 7.3 times more mutants than MDroid+. Therefore, the remaining time could be used by developers, practitioners, and servers to other software engineering activities. Additionally, as MutAPK generates more mutants, the generated search/bugs space might be more comprehensive, which means that the quality of the test suite can be tested in a more wide sense.

4.4 Analysis of non-compilable mutants

In order to understand the reasons for non-compilable mutants, we analyzed 3 mutants for each one of the mutant operators that generated non-compilable. It is worth noting that this process must be iterative and after finding and fixing the errors, the mutation process must be executed again.

4.4.1 31 - InvalidIDFindView

This operator generated more non-compilable mutants than others. For this operator we found there is an implementation error when the mutation was performed. The correct implementation should be to include *const <constVarName>, 0x<randomlyGeneratedHexa>* before the view was created to assign a random generated value to the key used as view ID. However, we injected *const/16 <constVarName>, 0x<randomlyGeneratedHexa>* that generated a packaging error due to specific instructions that must accompanying *const/16* and not *const*.

After this error was fixed the percentage of non-compilable mutants at app level without taking into account non-shared operators decreases to 4%.

4.4.2 27 - FindViewByIdReturnsNull

This operator presents two cases we did not consider. Listing 4.1 presents the SMALI representation for finding an Android view; the mutation rule asks to convert the result of the search into a null object. Therefore, Listing 4.2 presents the SMALI instruction that must be injected instead of the previous one to assign a null value to the result. Nevertheless, after the mutation is performed when the compilation process is launched, an error is displayed on the console (Listing 4.3), saying that all available registers are between 0 and 15. After a deeper analysis, we found that registers after 16 inclusive are used only for referencing values and a null value could not be assigned. Therefore, we found that a cumbersome process most be made and a verification of the value of the 16th available register must be performed to save the value while the result of the mutation is used, and then the original value can be reassigned to the used register.

This behavior was found in several mutants.

LISTING 4.1: SMALI representation of findByViewID method call

```
invoke-virtual {v0, v2},
    La2dp/Vol/main;->findViewById(I)Landroid/view/View;

move-result-object v21

check-cast v21, Landroid/widget/Button;
```

LISTING 4.2: SMALI representation of a null value being assigned

```
const/4 v21, 0x0
```

LISTING 4.3: APKTool console response

```
I: Using Apktool 2.3.2
I: Checking whether sources has changed...
I: Smaling smali folder into classes.dex...
test\smali\a2dp\Vol\main.smali[4027,4] Invalid register: v21. Must be
    between v0 and v15, inclusive.
Could not smali file: a2dp/Vol/main.smali
```

We found that last line of Listing 4.1 that is in charge of checking the type of the result, is not necessary and can be removed in some cases as it can be seen in Listing 4.4 . Therefore, our implementation search for that instruction to recognize the complete set of instructions that will be replaced. Therefore, MutAPK throws an error when trying to match this expression with next line.

LISTING 4.4: APKTool console response

```
invoke-virtual {v7, v9},
    Lcom/angrydoughnuts/android/alarmclock/ActivityAlarmNotification;->
        findViewById(I)Landroid/view/View;

move-result-object v7

invoke-virtual {v7, v12}, Landroid/view/View;->setVisibility(I)V
```

4.4.3 4 - InvalidKeyIntentPutExtra

Listing 4.5 shows the result of executing the compilation process over half of the mutants from this mutation operator that are non-compilable. As it can be seen in the listing, the process ends succesfully but no apk file is generated. At this

point we think that we might be facing an error within APKTool (*i.e., the tool used for assembling/disassembling an APK*).

LISTING 4.5: Example Output of MutAPK for PhotoStream app

```
I: Using Apktool 2.3.2
I: Checking whether sources has changed...
I: Smaling smali folder into classes.dex...
I: Checking whether resources has changed...
I: Building resources...
S: WARNING: Could not write to
   (C:\Users\Camilo\AppData\Local\apktool\framework), using
   C:\Users\Camilo\AppData\Local\Temp\ instead...
S: Please be aware this is a volatile directory and frameworks could
   go missing, please utilize --frame-path if the default storage
   directory is unavailable
I: Building apk file...
I: Copying unknown files/dir...
I: Built apk...
```

If these 4 mutant operators are updated and they do not generate non-compilable mutants, the percentage of non-compilable mutants at APK level (without taking into account the non-shared operators) should be dropped to 0.1%.

Chapter 5

Conclusion

We presented in this thesis a novel framework to enable automation of software engineering tasks at APK level through a proposed architecture presented in Section 3.1. Additionally, we validate its feasibility by implementing a Mutation Testing tool called MutAPK [**MutAPK**]. We evaluate the performance of MutAPK by comparing it with MDroid+, a Mutation Testing tool that works over source code. Our results show that MutAPK outperforms MDroid+ in terms of execution time, generating a testeable APK in a 6.28% of the time took by MDroid+. In terms of mutant generation MutAPK has a similar behavior to MDroid+ for the shared mutation operators generating about 17% more mutants (*i.e.*, around 30 more mutants per app). Nevertheless, MutAPK has implemented 2 operators not implemented yet by MDroid+, which enable the generation of about 85% of the mutants created. Therefore, MutAPK using this operators increases the difference to 739% more mutants (*i.e.*, around 1211 extra mutants per app).

Nevertheless, the mutation process done by MutAPK needs an improvement due to high rate of non-compilable mutants generated. In average, when using only the shared operators, 16% of the generated mutants by MutAPK are non-compilable and when all operators are used there are 2.36%. In this metric, MDroid outperforms MutAPK with only around 0.6% non-compilable mutants for both cases. Therefore, there is room for improvement because MutAPK should generate only compilable mutants, because it works on already compiled code from source code.

Finally, our results of the initial study with mutation testing suggest that in fact software engineering tasks can be enabled at APK level, and in the particular case of mutation testing we showed that working at APK level improves mutation testing times.

Chapter 6

Future Work

In this chapter we propose improvements and specialized tasks that could be done after this first stage of the research. First, a more comprehensive search of related work must be done to identify software engineering tasks that has been addressed using static analysis of android apps since 2016. Additionally, this further research can provide more information about the next to be implemented software engineering task (at APK level) in our pipeline, which could be either test cases generation, on-demand documentation, or another one.

At the same time, some effort must be dedicated to fully study the bug taxonomy generated by MDroid+ authors, in order to define more mutation operators or to propose other approaches to identify new possible bugs that could be translated into new mutation operators. Even more important, effort should be devoter to fix the high rate of non-compilable mutants that is generated by MutAPK.

Also, it will be helpful to build a wrapper for MutAPK (or a new tool) that is capable of orchestrating the execution of a test suite over the generated mutants. It is important for that solution to offer the possibility of deploying multiple AVD or similar representations and manage them taking into account different challenges as fragmentation, test flakiness, cold starts, etc. [**8094439**]

As an extension of the research question addressed in this thesis, an extensive study must be done using top applications of the different categories from the Google Play Store, to validate the behavior of MutAPK for more complex applications. Finally in terms of the implementation of MutAPK, some research effort can be invested in designing a model that improves the location recognition and provides enough information to continue mutating the SMALI representation in the registered times.