GIFdroid: Automated Replay of Visual Bug Reports for Android Apps

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ABSTRACT
Bug reports are vital for software maintenance that allow users to inform developers of the problems encountered while using software. However, it is difficult for non-technical users to write clear descriptions about the bug occurrence. Therefore, more and more users begin to record the screen for reporting bugs as it is easy to be created and contains detailed procedures triggering the bug. But it is still tedious and time-consuming for developers to reproduce the bug due to the length and unclear actions within the recording. To overcome these issues, we propose GIFdroid, a lightweight approach to automatically replay the execution trace from visual bug reports. GIFdroid adopts image processing techniques to extract the keyframes from the recording, map them to states in GUI Transitions Graph, and generate the execution trace of those states to trigger the bug. Our automated experiments and user study demonstrate its accuracy, efficiency, and usefulness of the approach.

CCS CONCEPTS
• Software and its engineering → Software testing and debugging.

KEYWORDS
bug replay, visual recording, android testing

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1 INTRODUCTION
Software maintenance activities are known to be generally expensive and challenging [60] and one of the most important maintenance tasks is to handle bug reports [17]. A good bug report is detailed with clear information about what happened and what the user expected to happen. It goes on to contain a reproduction step or stack trace to assist developers in reproducing the bug, and supplement information such as screenshots, error logs, and environments. As long as this bug report is accurate, it should be straightforward for developers to reproduce and fix.

Bugs are often encountered by non-technical users who will document a description of the bug with steps to reproduce it. However, clear and concise bug reporting takes time, especially for non-developer or non-tester users who do not have that expertise and are not willing to spend that much effort [18, 25]. A poorly written report would be even poorly interpreted [24, 26, 36], which often devolves into the familiar repetitive back and forth and the need to nag that comes with every single bug. That effort may further prohibit users’ contribution to bug reporting.

Compared to writing it down with instructions on how to replicate, video-based bug reports significantly lower the bar for documenting the bug. First, it is easy to record the screen as there are many tools available [3, 13], some of which are even embedded in the operating system by default like iOS [10] and Android [12]. Second, video recording can include more detail and context such as configurations, and parameters, hence it bridges the understanding gap between users and developers. That convenience may even better engage users in actively providing feedback to improve the app.

Despite the pros of the video-based bug report, it still requires developers to manually check each frame in the video and repeat it in their environment. According to our empirical study of 13,587 bug recordings from 647 Android apps in Section 2, one video is of 148.29 frames on average with a varied resolution for manual observation. In addition, only 6.8% of video recordings start from the app launch and most recordings begin 2-7 steps before the bug occurrence, indicating that developers need to guess steps to the entry frame of the video by themselves. Therefore, it is necessary to develop an automated bug replay tool from video-based bug reports to save developers’ effort in a bug fix.

There are many related works on bug replay but rarely related to visual bug reports. Some researchers [37, 65, 70, 83, 84] leverage the natural language processing methods with program analysis to generate the test cases from the textual descriptions in bug reports. However, those approaches do not apply to video-based bug reports. There are platforms providing both video recording and replaying functionalities [1, 23, 45, 62] which also store the low-level program execution information. They require the framework installation or app instrumentation which is too heavy for end users. Users tend to use general recording tools to get the video that only contains the visual information, according to our observation in Section 2.2. Automation for processing general recordings to reproduce bugs is necessary and would help developers shift their focus toward bug fixing.
To automate the analysis of bug recordings, we introduce GIFdroid, a light-weight image-processing approach to automatically replay the video (GIF) based bug reports for Android apps. First, we extract keyframes (i.e., fully rendered GUIs) of a recording by comparing the similarity of consecutive frames. Second, a sequence of located keyframes is then mapped to the GUI states in the existing UTG (UI Transition Graph) of the app by calculating image similarity based on pixel and structural features. Third, given the mapped sequence, we propose a novel algorithm to not only address the defective mapped sequence, but also auto-complete the missing trace between app launch to the entry frame of the video, resulting in an optimal execution trace to automatically repeat the bug trigger.

To evaluate the effectiveness of our tool, we create the groundtruth by manually labelling 61 video recordings from 31 apps. As our approach consists of three main components, we evaluate them one by one including keyframe location, GUI mapping, and trace generation. In all tasks, our approach significantly outperforms other baselines and successfully reproduce 82% video recordings. Apart from the accuracy of our tool, we also evaluate the usefulness of our tool by conducting a user study on replaying bugs from 10 real-world video recordings in GitHub. Through the study, we provide the initial evidence of the usefulness of GIFdroid for bootstrapping bug replay.

The contributions of this paper are as follows:

- The first light-weight image-processing based approach, GIFdroid, to reproduce bugs for Android apps directly from the GIF recordings with code released for public¹.
- A motivational empirical study of large-scale recordings within real-world issue reports from GitHub including their content, length, etc.
- A comprehensive evaluation including automated experiments and a user study to demonstrate the accuracy, efficiency and usefulness of our approach.

2 MOTIVATIONAL MINING STUDY

While the main focus and contribution of this work is developing an approach to automatically replay the visual bug reports, we still carry out an empirical study to understand the characteristics of visual bug reports. The overall status of visual bug reports can clearly frame the context and motivation of this work and their characteristics will be taken into consideration in our approach design. But note that this motivational study just aims to provide an initial analysis towards developers supporting visual bug reports, and a more comprehensive empirical study would be needed to deeply understand it.

2.1 Data Collection

We choose F-droid [5] as the source of our study subjects, as it contains a large set of apps (1,274 at the time of our study) covering diverse categories such as connectivity, financial, multimedia. All apps are open-source hosted on platforms like GitHub [8] which makes it possible for us to access their issue repositories for analysis.

We built a web crawler to automatically crawl the visual bug reports from issue repositories of these apps containing visual recordings (e.g., animation, video) with suffix names like .gif, .mp4, etc., or URL from video sharing platforms (e.g., GIPHY² [7], YouTube [15]).

It took us two weeks to scan 408,272 issues from 1,274 apps and finally mined 13,587 visual recordings from 7,230 issues (647 apps). The dataset consists of 8,698 GIFs and 4,889 videos. As shown in Figure 1, attaching visual recording in the issue report is more and more popular. Within the video, there is always some extra information (e.g., caption, whole screen of the PC, face of speaker) in addition to the app usage screen. Since there are more GIFs than videos, we focus on the GIF visual recording for brevity in this paper.

Figure 1: Number of recordings in GitHub from 2012 to 2020

Figure 2: Example of the issue reports for Bug Replay. The reporters provide a visual recording (i.e., gif) to help developers understand the bug report more clearly.

¹https://github.com/gifdroid/gifdroid

²GIPHY is the most popular animated GIF sharing platform, serving 700 million users
2.2 What are in Visual Recordings?

To understand the content within these visual recordings, the first two authors manually check 1,000 (11.5%) GIFs and their corresponding descriptions in the issue report. Following the Card Sorting [67] method, we classify those GIFs into three categories:

(i) Bug Replay (60%). Most screen recordings are about the bug replay including detailed procedures in triggering the bugs, especially for those requiring complicated actions with one example seen in Figure 2. The visual recordings bridge the lexical gap between users and developers and help developers read and comprehend the bug report reasoning about the problem from the high-level description.

(ii) Issue Fixed (17%). Once the issue is fixed, developers tend to record the screen to display the update changes, along with a checklist for project owners to approve the pull request. Also, those recordings are used for app introduction or answering users’ feature requests.

(iii) Feature Request (23%). Users may use recordings to ask for missing functionality (e.g., provided by other apps) or missing content (e.g., in catalogues and games), and sharing ideas on how to improve the app in future releases by adding or changing features.

2.3 What are Characteristics of Bug Recordings?

Since the target of this work is to auto-replay the bug recording, we further analyze the characteristics of 600 bug recordings classified in Section 2.2. Due to the difference of devices or users’ resize of the video, there may be different resolutions and aspect ratios as summarized in Table 1. About half of bug recordings are of 16:9 aspect ratio with varied resolution from high-quality 1920x1080 to 960x540. There are also some minor aspect ratios and resolutions as users may post-process the recording by resizing or cropping arbitrarily, according to our observation.

Figure 3 depicts the number of frames in visual bug recording. On average, there are 148.29 frames per video and some of them are even with more than 500 frames which require developers to manually check and replay in their own settings. We also find that only 41 recordings (6.8%) start from the launch of the app, while most recordings start from 2-7 steps before the bug occurrence. It indicates that there is no explicit hint to guide developers to the entry frame of the recording and that barrier may negatively influence developers’ efficiency. As the important information to show users’ actions, some recordings contain touch indicators (e.g., circle or arrow of the touch position) which is an important resource to replay the bug [23]. However, there are only 155 recordings (25.8%) enabling the “Show Touches” option in our dataset. Developers especially novice ones have to guess and try the potential actions to trigger the target page from the current page.

Table 1: Recording resolution.

| Ratios | Occurrences | Resolution     |
|--------|-------------|----------------|
| 16:9   | 288 (48%)   | 1920x1080      |
|        |             | 1280x720       |
|        |             | 960x540        |
| 5:3    | 63 (10.5%)  | 1280x800       |
|        |             | 800x480        |
| 3:2    | 21 (3.5%)   | 900x600        |
|        |             | 480x320        |

Summary: By analyzing issue reports from 1,274 existing apps crawled from F-Droid, 60% of them are with recordings for bug replay. A large number of frames and varied resolution make it difficult for developers to replay them in their setting. Such phenomenon is further exacerbated as 74.2% of recordings are without touch indicators on the screen. These findings confirm the necessity and difficulty of the replay of visual bug reports, and motivate our approach development for automatic replaying the recordings for developers and testers.

3 APPROACH

Given an input bug recording, we propose an automated approach to localize a sequence of keyframes in the GIF and subsequently map them to the existing UTG (UI Transition Graph) to extract the execution trace. The overview of our approach is shown in Figure 4, which is divided into three main phases: (i) the Keyframe Location phase, which identifies a sequence of keyframes of an input visual recording, (ii) the GUI Mapping phase that maps each located keyframe to the GUIs in UTG, yielding an index sequence, and (iii) the Execution Trace Generation phase that utilizes the index sequence to detect an optimal replayable execution trace.

3.1 Keyframe Location

Note that GUI rendering takes time, hence many frames in the visual recording are showing the partial rendering process. The goal of this phase is to locate keyframes i.e., states in which GUIs are fully rendered in a given visual recording.

3.1.1 Consecutive Frame Comparison. Inspired by signal processing, we leverage the image processing techniques to build a perceptual similarity score for consecutive frame comparison based on Y-Difference (or Y-Diff). YUV is a color space usually used in video encoding, enabling transmission errors or compression artifacts to be more efficiently masked by the human perception than using a RGB-representation [28, 68]. Y-Diff is the difference in Y (luminance) values of two images in the YUV color space. We adopt the luminance component as the human perception (a.k.a human vision) is sensitive to brightness changes. In the human visual system, a majority of visual information is conveyed by patterns of
contrasts from its brightness changes [79]. Furthermore, luminance is a major input for the human perception of motion [50]. Since people perceive a sequence of graphics changes as a motion, consecutive images are perceptually similar if people do not recognize any motions from the image frames.

Consider a visual recording \(\{f_0, f_1, \ldots, f_{N-1}, f_N\}\), where \(f_N\) is the current frame and \(f_{N-1}\) is the previous frame. To calculate the Y-Diff of the current frame \(f_N\) with the previous \(f_{N-1}\), we first obtain the luminance mask \(Y_{N-1}, Y_N\) by splitting the YUV color space converted by the RGB color space. Then, we apply the perceptual comparison metric, SSIM (Structural Similarity Index) [73], to produce a per-pixel similarity value related to the local difference in the average value, the variance, and the correlation of luminances.

In detail, the SSIM similarity for two luminance masks is defined as:

\[
SSIM(x, y) = \frac{(2\mu_x\mu_y + C_1) + (2\sigma_{xy} + C_2)}{\mu_x^2 + \mu_y^2 + \sigma_x^2 + \sigma_y^2 + C_1(C_2)}
\]

where \(x, y\) denote the luminance masks \(Y_{N-1}, Y_N\), and \(\mu_x, \sigma_x, \sigma_{xy}\) are the mean, standard deviation, and cross correlation between the images, respectively. \(C_1\) and \(C_2\) are used to avoid instability when the means and variances are close to zero. A SSIM score is a number between 0 and 1, and a higher value indicates a strong level of similarity.

3.1.2 Keyframe Identification. To make decisions on whether the frame is a keyframe, we look into the similarity scores of consecutive frames in the visual recording as shown in Figure 5. The first step is to group frames belonging to the same atomic activity according to a tailored pattern analysis. This procedure is necessary because discrete activities performed on the screen will persist across several frames, and thus, need to be grouped and segmented accordingly. There are 3 types of patterns, i.e., instantaneous transitions, animation transitions, and steady.

(1) instantaneous transitions: As shown in Figure 5 Activity 1 (clicking a button), the similarity score starts to drop drastically which reveals an instantaneous transition from one screen to another. In addition, one common case is that the similarity score becomes steady for a small period of time \(t_s\) between two drastically droppings as shown in Figure 5 Activity 3. The occurrence of this short steady duration \(t_s\) is because GUI has not finished loading. While the GUI layout of GUI rendering is fast, resources loading may take time. For example, rendering images from the web depends on device bandwidth, image loading efficiency, etc.

(2) animation transitions: Figure 5 Activity 2 shows the similarity sequence of the transitions where animation effects are used, for example, the "scrolling" event. That is, over a period of time, the similarity score continues to increase slightly.
taps" a button, the GUI transits to the GUI-3. There are many tools scrolls down" to the bottom of the page (GUI-2). When the user We have empirically set 0.95 77]. Therefore, instead of inferring actions from the recording [23, 4].

image distortion [46, 71]. To address this, we further supplement several fundamental limitations that exist in visual recordings, e.g., a detailed description is demonstrated in Section 3.1.1), it still has for the keyframe. BRIEF) [63], for searching the mapping GUI screenshots in the UTG structural Similarity Index) [73] and ORB (Oriented FAST and Rotated feature descriptors. We compute the similarity on luminance, contrast, and structure. We then further based on the features extracted by SSIM and ORB, we compute a similarity value $S_{ssim}$ and $S_{orb}$, respectively. To compute $S_{orb}$, we adopt the Brute Force algorithm [63], which compares the hamming distance between feature descriptors. We compute the $S_{ssim}$ using Equation 1 based on similarity on luminance, contrast, and structure. We then further determine the similarity $S_{comb}$ between the keyframe and states in UTG by combining two feature similarities score:

$S_{comb} = w \times S_{orb} + (1 - w) \times S_{ssim}$  

where $w$ is a weight for $S_{ssim}$ and $S_{orb}$, taking a value between 0 to 1. Smaller $w$ value weights $S_{ssim}$ more heavily, and larger value weights $S_{orb}$ more heavily. We empirically choose 0.5 as the $w$ value for the best performance.

Based on the combined similarity between the keyframe and each GUI screenshot, we select the highest score to be the index of the keyframe. Consequently, a sequence of keyframes is converted to a sequence of the index in the UTG.

3.3 Execution Trace Generation
After mapping keyframes to the GUIs in the UTG, we need to go one step further to connect these GUIs/states into a trace to replay the bug. However, this process is challenging due to two reasons. First, the extracted keyframe (Section 3.1) and mapped GUIs (Section 3.2) may not be 100% accurate, resulting in a mismatch of the groundtruth trace. For example in Figure 7, $\{D\}$ is missed in the index sequence 2 and the second keyframe is wrongly mapping to $\{B\}$, respectively.

(3) steady: Figure 5 gives an example of a GUI steady state where the consecutive frames are similar for a relatively long duration. We empirically choose 0.5 as the threshold to decide whether two frames are similar, and 5 frames as the threshold to indicate a steady state.

3.2 GUI Mapping
It is easy for developers to get the UTG of their own app [31, 77]. Therefore, instead of inferring actions from the recording [23, 80], we directly map keyframes extracted from the recording to states/GUIs within the UTG. To achieve this, we compute the image similarity between the keyframe and each GUI screenshot based on both pixel and structural features. The GUI screenshot that has the highest similarity score is regarded as the index of the keyframe.

3.2.1 UTG Construction. A GUI transitions graph (UTG) of an Android app is widely used to illustrate the transitions across different GUIs triggered by typical elements such as buttons (pop-ups), text boxes, text view objects, spinners, list items, progress bars, checkboxes. In Figure 6 we illustrate how a UTG emerges as a result of user interactions in an app. Starting with the GUI-1, the user “scrolls down” to the bottom of the page (GUI-2). When the user “taps” a button, the GUI transits to the GUI-3. There are many tools to construct a UTG, either manually [11] or automatically [19, 48]. In this paper, we adopt the Firebase [6], a widely-used automated GUI exploration tool developed by Google, while other tools can also be used.

3.2.2 Feature Extraction. The basic need for any image searching techniques is to detect and construct a discriminative feature representation [34, 35]. A proper construction of features can improve the performance of the image searching method [47]. According to our observation, in addition to the pixel features as that in natural images, GUI screenshots are also of additional structural features i.e., the layout of different components in one page. Therefore, we adopt a hybrid method based on two types of features, SSIM (Structural Similarity Index) [73] and ORB (Oriented FAST and Rotated BRIEF) [63], for searching the mapping GUI screenshots in the UTG for the keyframe.

While SSIM detects the features within pixels and structures (i.e., a detailed description is demonstrated in Section 3.1.1), it still has several fundamental limitations that exist in visual recordings, e.g., image distortion [46, 71]. To address this, we further supplement a local invariant feature extraction method, ORB. Given an image, we set up that value by a small-scale pilot study.

Figure 6: An example of partial UTG on mobile app GUI proceeding from state GUI-1 to state GUI-3.

Figure 7: Illustration of the execution trace generation. Index sequence 2,3 indicate two types of defective sequences, i.e., missing $\{D\}$ and wrong mapping to $\{B\}$, respectively.
to \{B\} in the index sequence 3. Second, different from the uploaded GIF which may start the recording anytime, the recovered trace in our case must begin from the launch of the app.

Therefore, the trace generation algorithm needs to consider both the wrong extraction/mapping in our previous steps, and the missing trace between the app launch and first keyframe in the visual bug report. To overcome these issues, our approach first generates all candidate sequences in UTG between the app launch to the last keyframe from GIF. By regarding the extracted keyframes as a sequence, our approach then further extracts the Longest Common Subsequence (LCS) between it and all candidate sequences.

The overflow of our approach can be seen in Algorithm 1. Given an index sequence \(X = \{x_1, x_2, ..., x_n\}\) (extracted by keyframe mapping) where \(x_n\) is the last node, a UTG graph \(G\), and an app launch node \(s\). To find acyclic paths (avoiding dead loops) from app launch node \(s\) to last index node \(x_n\), we adopt Depth-First Search traversal, that takes a path on \(G\) and starts walking on it and check if it reaches the destination then count the path and backtrack to take another path. To avoid cyclic path, we record all visited nodes (Line 5), so that one node cannot be visited twice. The output of the traversal is a set of acyclic path \(SEQ = \{y_1, y_2, ..., y_m\}\) where \(y_1 = s\) and \(y_m = x_n\). We regard those acyclic paths as the candidate traces for execution. For example, in Figure 7, there are three candidate sequences from launch node \(A\) to last index node \(F\) are found (1)\{(A, B, C, D, E, F)\}, (2)\{(A, B, C, H, I, F)\}, (3)\{(A, B, C, H, I, E, F)\}. Note that \(\{A, B, C, D, E, D, E, F\}\) is omitted due to cyclic.

Next, for each candidate sequence \(SEQ\), we adopt the dynamic programming algorithm to find the LCS to the index sequence \(X\) (Lines 17-32), in respect to detect how many index nodes are covered in this candidate sequence. The recursive solution to detect the LCS for each candidate sequence \(SEQ\) to index sequence \(X\) can be defined as:

\[
com[i, j] = \begin{cases} 
0 & \text{if } i = 0 \text{ or } j = 0 \\
com[i-1,j-1]+1 & \text{if } x[i] = seq[j] \\
\max(com[i-1,j],com[i,j-1]) & \text{if } x[i] \neq seq[j]
\end{cases}
\]

where \(com\) to be a table for \(X\) and \(SEQ\) (e.g., \(com[i, j]\) is the relation between \(X_i\) and \(SEQ_j\)). A LCS can be found by tracing the table \(com\). We omit the details of tracing the table as \(\text{FindLCS}(com)\) due to space limitations. Note that we initialize first row and column of \(com\) as zero to prevent the occurrence of NULL (Line 19). For example, in Figure 7, the LCSs between index sequence and three candidate sequences are (1)\{(C, E, F)\} (2)\{(C, F)\} (3)\{(C, E, F)\}, respectively.

Once the LCSs are detected, we select the candidate sequence that has the longest LCS as the execution trace due to it replays most keyframes (or index nodes) in the visual recording. Besides, our goal is to help developers reproduce the bug with the least amount of time/steps. Therefore, we choose the optimal execution trace with the shortest sequence. For example, in Figure 7, (2)\{(A, B, C, H, I, F)\} is omitted due to it does not replay the most index nodes, (i.e., its LCS \(\{C, F\}\) is not the longest). (3)\{(A, B, C, H, I, E, F)\} is omitted due to it is not the optimal trace (i.e., not the shortest sequence). Therefore, the optimal execution trace (1)\{(A, B, C, D, E, F)\} is generated based on the index sequence, even defective.

\section{Automated Evaluation of GIFDroid}

In this section, we describe the procedure we used to evaluate GIFDroid in terms of its performance automatically. We manually construct a dataset as the groundtruth for evaluating each step within our approach. We collect 61 visual recordings from
31 open-source Android apps which were used in previous studies [25, 26, 55]. They are also top-rated on Google Play covering 14 app categories (e.g., finance, productivity, etc.). To make these recordings as similar to real-world bug reports as possible, we adopt different ways for generating the recording including different creation tools (32 from video conversion, 22 from mobile apps, 7 from emulator screen recording), varied resolutions (27 1920 × 1080, 23 1280 × 800, 11 900 × 600), diverse length (30-305 frames), and differed playing speed (7-30 frames per second).

For each app, we also collect its UTG by Google Firebase. Since our approach consists of three main steps, we evaluate each phase of GIFdroid, including Keyframe Location (Section 3.1), GUI Mapping (Section 3.2), and Execution Trace Generation (Section 3.3). Therefore, we ask two experienced developers to manually label keyframes from recordings, GUI mapping between recording and UTG, and real trace in the UTG as the groundtruth for each phase. Note that each human annotator finished the labelling individually and they discussed the difference until an agreement was reached.

### 4.1 Accuracy of Keyframe Location

**Ground Truth:** To evaluate the ability of keyframe location to accurately identify the keyframes present in the visual recordings, we manually generated a ground truth for the keyframe. We recruited two paid annotators from online posting who have experience in bug replay. To help ensure the validity and consistency of the ground truth, we first asked them to spend twenty minutes reading through the video annotation guidelines (i.e., TRECVID [58]) and get familiar with the widely-used annotation tool VirtualDub [14]. Then, we assigned the set of visual recordings to them to annotate keyframes independently without any discussion. After the annotation, the annotators met and sanity corrected the subtle discrepancies (i.e., ± 3 frames). Any disagreement would be handed over to one author for the final decision. In total, we obtained 289 keyframes for 61 recordings, 4.73 per recording on average, tallying over to one author for the final decision. In total, we obtained 289 ground truth pairs of keyframes and GUI screenshots.

**Metrics:** We employ three evaluation metrics, i.e., precision, recall, F1-score, to evaluate the performance of keyframe location. The predicted frame which lies in the ground truth interval is regarded as correctly predicted. Since there should be only one keyframe per interval, if two or more keyframes are localized in a single interval, only the first keyframe is counted as correct. Recall is the proportion of frames that are correctly predicted as keyframes among all frames predicted as keyframes.

\[
\text{precision} = \frac{\# \text{Frames correctly predicted as keyframes}}{\# \text{All frames predicted as keyframes}}
\]

Recall is the proportion of frames that are correctly predicted as keyframes among all keyframes.

\[
\text{recall} = \frac{\# \text{Frames correctly predicted as keyframes}}{\# \text{All keyframes}}
\]

F1-score (F-score or F-measure) is the harmonic mean of precision and recall, which combine both of the two metrics above.

\[
F1 - \text{score} = \frac{2 \times \text{precision} \times \text{recall}}{\text{precision} + \text{recall}}
\]

For all metrics, a higher value represents better performance.

### 4.2 Accuracy of GUI Mapping

**Ground Truth:** To evaluate the ability of GUI mapping to accurately search the nearest GUI screenshot in the UTG, we first collected the UTG and their GUI screenshots for those apps, following the procedure outlined in Section 3.2.1. Given the keyframes (i.e., a frame from the ground truth interval), we selected the most similar GUI screenshot in the UTG as the ground truth for GUI mapping. Note that labelling was finished by two annotators independently without any discussion, and any disagreement would be handed over to one author for the final decision. Thus, we obtained 289 ground truth pairs of keyframes and GUI screenshots.

**Baselines:** We set up four state-of-the-art methods which are widely used for keyframe extraction as the baselines to compare with our method. Comixify [59] is an unsupervised reinforcement learning method to predict for each frame a probability to extract keyframes in the videos. ILS-SUMM [64] formulates the keyframe extraction as an optimization problem, using a meta-heuristic optimization framework to extract a sequence of keyframes that has minimum feature distance. Hecate [66] is a tool developed by Yahoo that estimates frame quality on the image aesthetics and clusters them to select the centroid as a keyframe. PySceneDetect [9] is a practical tool implemented as a Python library that is popular in GitHub. The core technique for PySceneDetect to detect keyframes is a content-aware detection by analyzing the color, intensity, motion between frames.

**Results:** Table 2 shows the performance of all approaches. The performance of our method is much better than that of other baselines, i.e., 32%, 106%, 14% boost in recall, precision, and F1-score compared with the best baseline (ILS-SUMM, PySceneDetect). The issues with these baselines are that they are designed for general videos which contain more natural scenes like human, plants, animals etc. However, different from those videos, our visual bug recordings belong to artificial artifacts with different rendering processes. Therefore, considering the characteristics of visual bug recordings, our approach can work well in extracting keyframes.

Our approach also makes mistakes in keyframe extraction due to three reasons. First, within some apps, the resource loading is so slow that the partial GUI may stay for a relatively long time, beyond our threshold setting in Section 3.1. So, that frame is wrongly predicted as a keyframe. Second, some users may click the button before the GUI is fully rendered to the next page. That short period makes our approach miss the keyframe. Third, some GUIs may contain animated app elements such as advertisement or movie playing, which will change dynamically, resulting in no steady keyframes being localized.

### Table 2: Performance comparison for keyframe location.

| Method       | Precision | Recall | F1-score |
|--------------|-----------|--------|----------|
| Comixify [59]| 0.244     | 0.516  | 0.332    |
| ILS-SUMM [64]| 0.255     | 0.685  | 0.371    |
| PySceneDetect [9] | 0.418 | 0.550  | 0.475    |
| GIFdroid     | 0.858     | 0.904  | 0.880    |
Table 3: Performance comparison for GUI Mapping

| Metric      | Pixel | Structure | GIFdroid |
|-------------|-------|-----------|----------|
| Precision@1 | 0.0%  | 30.6%     | 63.6%    |
| Precision@2 | 1.3%  | 47.7%     | 81.3%    |
| Precision@3 | 1.3%  | 55.7%     | 85.3%    |

Results: Table 3 shows the overall performance of all methods. In contrast with baselines, our method outperforms in all metrics, 85.4%, 90.0%, 91.3% for Precision@1, Precision@2, Precision@3 respectively. We observe that the methods based on structural features perform much better than pixel features due to the reason that the pixel similarity suffers from the scale-invariant as the resolutions for visual recordings varies. Our method that combines SSIM and ORB leads to a substantial improvement (i.e., 9.7% higher) over any single feature, indicating that they complement each other. In detail, ORB addresses the image distortion that causes false GUI mapping considering only SSIM.

4.3 Performance of Trace Generation

Ground Truth: To evaluate the ability of trace generation to accurately generate the replayable execution trace, we label the execution trace that can replay the visual recording from the app launch as the ground truth. Note that there may be multiple ground truth traces complying with the optimal definition (i.e., the shortest trace to replay the recording) in Section 3.3. Therefore, we manually check and label all the ground truths by two annotators independently without any discussion. To ensure the quality, any disagreement would be handed over to one author for the final decision. Totally, we obtained 61 execution traces, including 539 reproduction steps.

Metrics: To measure the similarity of the groundtruth trace and predicted replay sequence, we first get the LCS between two sequences. We then calculate the similarity [75] following $\frac{\sum \text{sequence}}{\text{sequence}}$ where $M$ is the length of LCS, and $T$ is the length of the sum of both sequences. It gives a real value with a range [0,1] and is usually expressed as a percentage. The higher the metric score, the more similar the generated execution trace is to the ground truth. If the generated trace exactly matches the ground truth, the similarity value is 1 (100%).

Baselines: We setup one state-of-the-art scenario generation method (V2S) and an ablation study of GIFdroid without LCS algorithm (GIFdroid-LCS) as our baselines. V2S [23] is the first purely graphical Android record-and-replay technique. V2S adopts deep learning models to detect user actions via classifying touch indicators for each frame in a video, and converts these into a script to replay the scenarios. Note that V2S has strict requirements about the input video including high resolution, frames per second and touch indicator for inferring detailed actions. Therefore, in addition to testing V2S in all our datasets, we also test its performance in the part of our dataset (i.e., 19 recordings) which contain touch indicators called V2S+Touch. To test the importance of the proposed algorithm that addresses defective index sequence in Section 3.3, we also add another ablation study called GIFdroid-LCS which does not contain that component.

Results: Table 4 shows the performance comparison with the baselines. Our method achieves 89.59% sequence similarity which is much higher than that of baselines. Note that due to the strict
Table 5: Detailed results for execution trace generations. Green cells indicate fully reproduced recordings, orange cells > 50% reproduced, and red cells < 50%.

| AppName     | Rep. Trace | AppName     | Rep. Trace | AppName     | Rep. Trace | AppName     | Rep. Trace | AppName     | Rep. Trace |
|-------------|------------|-------------|------------|-------------|------------|-------------|------------|-------------|------------|
| Token       | 8/8        | TimeTracker | 10/10      | TrackerControl | 23/24      | YoloSec     | 9/9        |             |
| DeadFlash   | 25/25      | GNUCash     | 9/9        | aFreeRDP    | 11/11      | AntennaPod  | 7/7        |             |
| ProtonVPN   | 7/7        | FastNFitness| 8/8        | JioFi       | 6/6        | WiFiAnalyzer| 9/9        |             |
| PSLab       | 8/9        | DroidWeight  | 6/6        | openScale   | 18/18      | KeePassDX   | 6/6        |             |
| Trigger     | 7/7        | ADBungFu    | 2/8        | EteSyncNotes| 11/11      | PortAuthority| 8/8        |             |
| ATime       | 7/7        | AdAway      | 8/8        | StinglePhoto| 7/7        | InviZible   | 6/6        |             |

Figure 9: Illustration of bad case for trace generation. Black line represents ground truth. Red line represents the generated execution trace.

requirement of input recordings, V2S does not work well in all our datasets, but performs well in our partial dataset with touch indicators. Even for recordings with touch indicators, the extracted trace is still not that accurate as it could not recover the trace from the app launch to the entry in the recording. In a word, the hard requirements still limit its generality in the real testing environment especially those open-source software development. In addition, adding LCS can mitigate the errors introduced in the first two steps in our approach, resulting in a boost of performance from 82.63% to 89.59%. Although applying LCS takes a bit more runtime (i.e., 13.25 seconds on average), it does not influence its real-world usage as it can be automatically run offline.

Table 5 shows detailed results of the success rate for each visual recordings, where each app, execution trace (number of steps), and successfully replayed steps are displayed. Green cells indicate a fully reproduced execution trace from the video recording, Orange cells indicate more than 50% of steps reproduced, and Red cells indicate less than 50% of reproduced steps. GIFdroid fully reproduces 82% (50/61) of the visual recordings, signals a strong replay-ability. We manually check the instances where our method failed to reproduce scenarios. Instances where slightly biased (orange cells) are largely due to inaccuracies in keyframe location (i.e., in Figure 9(a), [B] is missing) and GUI mapping (i.e., in Figure 9(b), [B] is incorrectly mapping to [D])). Instances that failed to reproduce (red cells) are due to the inaccuracies on the last index as our method depends on the last index to end the search (i.e., in Figure 9(c), we search the execution trace on [E]).

5 USEFULNESS EVALUATION

We conduct a user study to evaluate the usefulness of the generated execution trace for replaying visual bug recording into real-world development environments. We recruit 8 participants including 6 graduate students (4 Master, 2 Ph.D) and 2 software developers to participate in the experiment. All students have at least one-year experience in developing Android apps and have worked on at least one Android apps project as interns in the company. Two software developers are more professional and work in a large company (Alibaba) about Android development.

Procedure: We first give them an introduction to our study and also a real example to try. Each participant is then asked to reproduce the same set of 10 randomly selected visual bug recordings from GitHub which are of diverse difficulty ranging from 6 to 11 steps until triggering bugs. Detailed experiment dataset can be seen in our online appendix\(^3\). The study involves two groups of four participants: the experimental group \(P_1, P_2, P_3, P_4\) who gets help with the generated execution trace by our tool, and the control group \(P_5, P_6, P_7, P_8\) who starts from scratch. Each pair of participants \(\langle P_x, P_{x+1}\rangle\) have comparable development experience, so that the experimental group has similar capability to the control group in total. Note that we do not ask participants to finish half of the tasks with our tool while the other half without assisting tool to avoid potential tool bias. We record the time used to reproduce the visual bug recordings in Android. Participants have up to 10 minutes for each bug replay.

Results: Table 6 shows the experiment result. Although most participants from both experimental and control groups can successfully finish the bug replay on time, the experiment group reproduces

Table 6: Performance comparison between the experimental and control group. * denotes \(p < 0.01\).

| AppName     | Control Group | Experimental Group |
|-------------|---------------|--------------------|
|             | Success Time (sec) | Success Time (sec) |
| AnkDroid-1  | 2/4           | 437                |
| AnkDroid-2  | 3/4           | 334                |
| KISS-1      | 4/4           | 121                |
| NeuroLab-1  | 4/4           | 90                 |
| NeuroLab-2  | 4/4           | 366                |
| BeHe-1      | 4/4           | 77                 |
| BeHe-2      | 4/4           | 94                 |
| AndoOBBD-1  | 4/4           | 63                 |
| PDFConverter-1 | 4/4 | 71               |
| PDFConverter-2 | 4/4 | 25               |
| Average     | 3.7/4         | 171.4              |
|             | 4/4           | 65.0*              |

\(^3\)https://sites.google.com/view/gifdroid
the visual bug recording much faster than that of the control group (with an average of 171.4 seconds versus 65.0 seconds). In fact, the average time of the control group is underestimated, because three bugs fail to be reproduced within 10 minutes, which means that participants may need more time. In contrast, all participants in the experiment group finish all the tasks within 2 minutes. To understand the significance of the differences between the two groups, we carry out the Mann-Whitney U test [54] (specifically designed for small samples) on the replaying time. The testing result suggests that our tool can significantly help the experimental group reproduce bug recordings more efficiently (p-value < 0.01).

We summarise two reasons why it takes the control group more time to finish the reproduction than the experiment group. First, some visual recording is quite complicated which requires participants in the control group to watch the visual recordings several times for following procedures. The GUI transitions within the recording may also be too fast to follow, so developers have to replay it. Second, it is hard to determine the trigger from one GUI to the next one. As illustrated in Section 2.3, only 25% of videos are recorded with the touch indicator, resulting in developers' guess of the action for triggering the next GUI. That trial and error makes the bug replay process tedious and time-consuming. It is especially severe for junior developers who are not familiar with the app code.

6 RELATED WORK

A growing body of tools has been dedicated to assisting in recording and replaying bugs in mobile and web apps. We introduce related works of bug replay based on different types of information including the app running information, textual description, and visual recording in this section.

6.1 Bug Record and Replay from App Running Information

Nurmuradov et al. [57] introduced a record and replay tool for Android applications that captures user interactions by displaying the device screen in a web browser. It used event data captured during the recording process to generate a heatmap that facilitates developers understanding of how users are interacting with an application. Additional tools including ECHO [69], Reran [39], Barista [42], and Android Bot Maker [2] are program-analysis related applications for the developer to record and replay interactions. However, they required the installation of underlying frameworks such as replaykit [4], troyd [40], or instrumenting apps which is too heavy for end users. In contrast to these approaches, our GIFdroid is rather lightweight which just requires the input recording and UTG which can be generated by existing tools.

6.2 Bug Replay from Textual Information

To lower the usage barrier of record and replay that requires frameworks, many of the studies [22, 37, 41, 55, 74] facilitate the bug replay base on the natural language descriptions in bug report which contains immediately actionable knowledge (e.g., reliable reproduction steps), stack traces, test cases, etc. For example, ReCODroid [84] leveraged the lexical knowledge in the bug reports and proposed a natural language processing (NLP) method to automatically reproduce crashes. However, it highly depended on the description writing in the bug report including formatting, word usage, granularity [24, 36, 43] which limit its deployment in the real world. Many works that assist developers in writing bug reports [51, 53, 55, 56] still cannot directly benefit it. Different from textual bug reports, visual recordings contain more bug details and can be easily created by non-technical users. Therefore, our work focuses on the automated bug replay from these visual bug reports.

6.3 Bug Replay from Visual Information

In software engineering, there are many works on visual artifacts including recording, tutorials, bug reports [27, 29, 32, 38, 61, 78, 82] with some of them specifically for usability and accessibility testing [30, 49, 76, 81]. In detail, Bao et al. [20] focused on the extraction of user interactions to facilitate behavioral analysis of developers during programming tasks, such as code editing, text selection, and window scrolling. Krieter et al. [44] analyzed every single frame of a video to generate log files that describe what events are happening at the app level (e.g., the ‘k’ key is pressed). Different from these works in extracting developers’ behavior, our work is concerned with the automated bug replay from the recording in the bug report.

Bernal et al [23] proposed a tool named V2S which leverages deep learning techniques to detect and classify user actions (e.g., a touch indicator that gives visual feedback when a user presses on the device screen) captured in a video recording, and translate it into a replayable test script. Although the target of this work is the same as ours, there are two major differences between them. First, V2S requires high-resolution recording with touch indicators which is hard to get in real-world bug reports according to our analysis (less than 25.8%) in Section 2.2. Second, it requires complete recording from the app launch to the bug occurrence while most recordings (93.2%) in the real world do not start from the app launch, but just 2-7 steps before the bug page. In contrast, our approach design is fully driven by the practical data, hence it does not have those requirements. The user study of real-world bug replay also confirms the usefulness and generality of our approach.

7 CONCLUSION

The visual bug recording is trending in bug reports due to its easy creation and rich information. To help developers automatically reproduce those bugs, we propose GIFdroid, an image-processing approach to covert the recording to executable trace to trigger the bug in the Android app. Our automated evaluation shows that our GIFdroid can successfully reproduce 82% (50/61) visual recordings from 31 Android apps. The user study on replaying 10 real-world visual bug recordings confirms the usefulness of our GIFdroid in boosting developers’ productivity.

In the future, we will keep improving our method for better performance in term of keyframe extraction, GUI mapping, and trace generation. To make GIFdroid more usable, we will also take the human factor into the consideration. As the automated approach may not be perfect, we will further explore how human
can collaborate with the machine for replacing the bugs in the visual bug report.

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