A Survey of Field-based Testing Techniques

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Field testing refers to testing techniques that operate in the field to reveal those faults that escape in-house testing. Field testing techniques are becoming increasingly popular with the growing complexity of contemporary software systems. In this article, we present the first systematic survey of field testing approaches over a body of 80 collected studies, and propose their categorization based on the environment and the system on which field testing is performed. We discuss four research questions addressing *how* software is tested in the field, *what* is tested in the field, which are the *requirements*, and how field tests are *managed*, and identify many challenging research directions.

CCS Concepts: • **Software and its engineering → Software testing and debugging**;

Additional Key Words and Phrases: Software testing, field testing, in-vivo testing, ex-vivo testing

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1 INTRODUCTION

Software testing involves a set of pervasive, critical, time-consuming, and effort-demanding activities in the software lifecycle. It is widely practiced and extensively studied [85].

Testing activities are commonly conducted on a **Software Under Test (SUT)** during the development cycle to both reveal faults before deployment and study failures reported from the field. No matter whether testing activities aim to reveal development bugs or study field failures, they are commonly executed in the development environment, and we refer to such activities as *in-house* or *in-vitro* software testing. In-vitro testing is generally conducted independently from the production context, except for the failures reported from the field, which may trigger in-house testing activities. Indeed, field failures cannot be fully prevented, and may sometime lead to catastrophic consequences. A recent study by Gazzola et al. [39] identifies several categories of field failures, and provides empirical evidence of the unavoidability of failures in the field even for mature and well-tested software systems.

The impossibility of dealing with all the faults using classic in-house testing approaches raised interest in testing software systems in the field, by crossing the border between in-house validation and field execution [7]. As we illustrate in Figure 1, this trend of moving the testing activities from the laboratory toward the production environment can be actualized in different nuances. Test cases can be executed directly in the field on the same instance of the software used in production, which we call *online testing* (rightmost flow of activities in Figure 1), or on a separated instance still running in production, called *offline testing* (middle flow), or even in-house but on data collected from the field, called *ex-vivo testing* (leftmost flow).

Classic in-house (in-vitro) testing is a well understood discipline with studies that span many decades: The first specialized workshop dates back to the mid seventies.[1] Research in field testing has emerged fairly recently and has not been comprehensively surveyed as a discipline yet.

Field testing was first considered an opportunity to deal with failures that were hard or too costly to reproduce in the laboratory, with a few studies in the nineties addressing autonomic systems [51, 100], and real-time issues [99]. It attracted then steady interest in the early years of the first decade of this century, with a sudden burst of results from 2007 on, mostly pushed by the advent of service-oriented architectures, which lacked centralized control for testing purposes.

Nowadays, the emergence of more and more agile and distributed paradigms of development, toward the view of a *continuous software engineering* discipline [35], emphasizes the need for a *continuous testing* mindset, making developers realize that testing must continue after deployment, and that no clear boundary can be set between development and operation [7]. Such a need, in combination with the increasing dynamism and pervasiveness of software, as observed, for instance, in Internet of Things, Systems of Systems, and Cyber-Physical systems, led to a relevant set of approaches and frameworks for field testing, although not well contextualized yet. In particular, while inheriting many of the problems and solutions of its "traditional" counterpart, field testing obviously introduces new challenges, for example in terms of isolation from side effects, security preservation, controllability and observability of the test executions, among others. For these reasons, a systematic study of the literature is required to rise awareness of the topic and provide evidence for the need of further research.

To answer such need, in this article we provide a comprehensive survey of the state-of-the-art of ex-vivo, offline, and online field testing approaches. We present the results of a systematic analysis of the scientific literature that identified 80 distinct relevant studies since 1989. We discuss the characteristics of the different approaches, and propose a taxonomy based on the environ-

[1] The ISSTA community refers back to the former TAV community with roots in the 1975 Workshop on Currently Available Program Testing Tools.

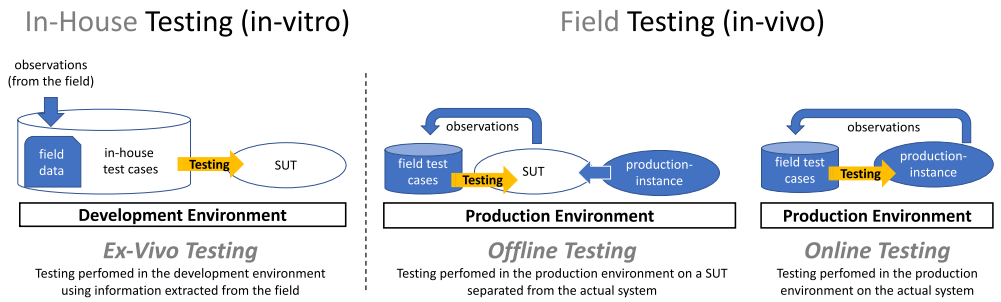

Fig. 1. Classes of field testing approaches.

ment and the system where the test cases are generated and executed. We distinguish between approaches that address *functional* and *non-functional* faults, and observe that the relatively few ex-vivo and offline field testing approaches address functional faults, while the many online field testing approaches span from functional to non-functional faults.[2]

We survey the approaches for field testing, and for each class of approaches we systematically discuss their characteristics based on four main research questions that guide our effort throughout this survey. In particular, we consider *how* software is tested in the field, *what* is tested in the field, the *requirements* to successfully execute the tests in the field, and the *management* of the field tests.

The remainder of the article is organized as follows. Section 2 discusses the methodology of the survey, providing details about the process that we followed to select the relevant studies and the corresponding statistics. Section 3 introduces the key concepts and the terminology that we use in the article and frames the boundaries of our analysis. Section 4 introduces the research questions that we address in this article, and that we discuss in Sections 5–9. Section 10 summarizes the state of the art in field testing, indicates relevant open research directions and presents guidelines for practitioners. Section 11 discusses threats to validity. Section 12 provides final remarks.

2 METHODOLOGY

In this section, we present the methodology that we followed to identify the relevant papers in line with the best practices by Kitchenham et al. [56].

2.1 Selection Process

The aim of this survey is to provide a comprehensive summary of the scientific literature on field testing and propose a taxonomy of the approaches. Our research questions, which we describe later on after we have introduced the needed background and terminology, are broad and inclusive. Accordingly, in our search strategy we aimed at a search string wide enough to represent all the many ways researchers may indicate field testing related work, as detailed below:

(1) Initial search and first-stage filtering. An initial set of papers was selected by searching the *SciVerse Scopus* digital library with the following search string. We selected all papers whose title, abstract or keywords match any of the keywords in the query:

```
(Runtime testing OR Online testing OR On-line testing OR Dynamic testing OR
Adaptive testing OR Field testing OR On-demand testing OR In-vivo testing
OR Ex-vivo testing) AND software
```

[2]In this article we use the terms *failures*, to indicate executions that lead to wrong results, and *faults*, and sometime the common jargon term *bugs*, to indicate issues in the code that may cause the system to fail under specific execution conditions, in line with the IEEE standard terminology.

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OR
(Runtime software testing OR Online software testing OR On-line software
testing OR Dynamic software testing OR Adaptive software testing OR Field
software testing OR On-demand software testing OR In-vivo software testing
OR Ex-vivo software testing).
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The initial search produced a set of 1,238 studies. Due to the conservative query, the initial set of papers included many papers not related to computer science, and artifacts of different nature, research articles, editorials, standards, and welcome messages. We pruned both papers clearly not related to computer science, and irrelevant artifacts, such as editorials, standards, welcome messages, by manually inspecting titles and abstracts, and we obtained a set of 434 studies.

(2) Selection criteria. We refined the obtained set of papers with inclusion and exclusion criteria, to retain scientific studies about software field testing, and eliminate papers that address neither software nor field testing. We retained papers that satisfy all the following inclusion criteria:

- *Inclusion Criterion 1*: studies targeting the definition, application or experimentation of software field testing solutions.
- *Inclusion Criterion 2*: studies subject to peer review.
- *Inclusion Criterion 3*: studies written in English.

and discarded papers that meet at least one of the following exclusion criteria:

- *Exclusion Criterion 1*: studies proposing field testing solutions not related to software systems, such as firmware or hardware testing, including processors, systems-on-chip, FPGA, and controllers.
- *Exclusion Criterion 2*: studies purely focusing on techniques other than testing, most notably we exclude works centered on: runtime verification [68], or debugging, even approaches for debugging in the field such as [65], or continuous experimentation via user surveys [90] and A/B testing [57], or usability evaluation [49, 97].
- *Exclusion Criterion 3*: studies that move testing away from the developer's laboratory to improve scalability and elasticity, but with no specific focus on field operation: for example, we exclude works proposing Testing-as-a-Service and Cloud testing solutions [11].
- *Exclusion Criterion 4*: studies focusing on the interleaving/adjustement of test generation to test execution (which sometimes is also referred in literature as "online" or "adaptive" testing, keywords included in our search), but have no relation with the field, e.g., on-the-fly model based testing [96], or those works that dynamically adjust the testing strategy using testing results, such as [19].
- *Exclusion Criterion 5*: studies about in-house operational profile-based testing [91]: Although operational testing refers to how the system is used in the field, this topic has been the subject of an extensive literature that has evolved independently from the notion of testing in the field.
- *Exclusion Criterion 6*: studies about crowdsourced testing: testing performed by the crowd on released software could be considered as a specific form of testing in the field; however, we decided not to include them in this study, also because for this topic we can refer the reader to a recently appeared systematic review of literature [4].
- *Exclusion Criterion 7*: secondary or tertiary studies (e.g., systematic literature reviews and surveys).
- *Exclusion Criterion 8*: studies not available as full-text.

In a first pass, the authors of this survey independently assessed the 434 papers, and classified them as "Included," "Excluded," and "Unclear," based on the inspection of title, abstract, and publication venue. We excluded 334 papers, included 34, and identified 66 unclear papers for further analysis. Then, we collaboratively classified the 66 papers, by reading the full papers, and discussing them in dedicated conference calls. We included 14 more papers, ending up with 48 selected papers.

(3) Snowballing. We completed the selection process with a snowballing procedure. We applied a full *backward snowballing*, by considering all the references included in the analyzed studies, and adding further relevant studies, provided they were indexed by at least one of these major digital libraries: *SciVerse Scopus*, *IEEEXplore*, and *ACM DL*. We conducted a partial *forward snowballing* starting from the most popular papers selected so far. In particular, we selected both the 10% most cited papers and the top 10% of the papers with the highest number of *normalized* citations (i.e., citation/year), identifying a total of 12 highly popular studies. We considered all the papers that cite at least one of the identified popular studies, obtaining 71 possibly relevant studies. We pruned this set with the inclusion and exclusion criteria, and added 32 new papers to our set of papers.

The process produced a set of **80 studies for our survey.** During this process, we scheduled six plenary (physical or online) meetings in one year to define the include and exclude criteria, to discuss the studies, and to clarify and resolve doubtful cases.

2.2 Data Extraction

We identified several dimensions for analyzing the selected papers, based on the research questions presented in Section 4. For each paper, we checked if the presented study could be classified according to each identified dimension, and when possible we produced such a classification. We describe the studies and the analyzed dimensions in Sections 5–9.

We tuned the analysis process by assigning a small set of papers (14/80) to multiple authors, to obtain redundant classifications for each paper, and then discussing the results of the classifications in a plenary meeting. In the plenary meeting we agreed on the semantics of each dimension, and the criteria for classifying the papers. We relied on the results of the plenary meeting to safely distribute the analysis of the remaining papers to subsets of authors who worked in parallel.

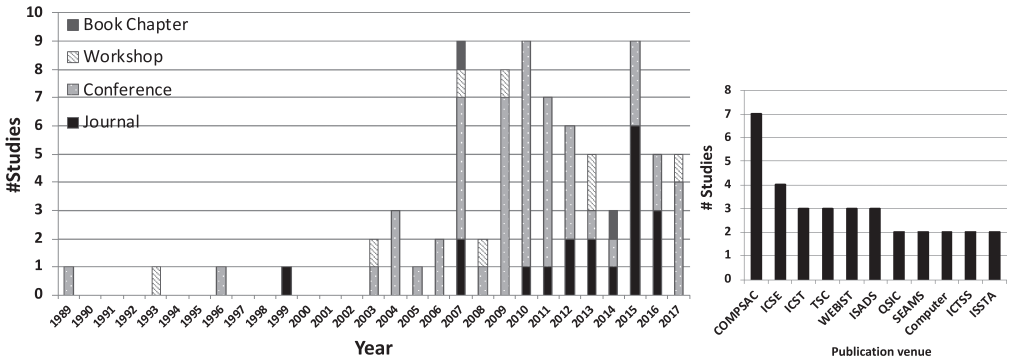
2.3 Descriptive Statistics

The data collection was performed in 2018. The search period was not constrained; the time period of the resulting papers, after filtering and classifications, was 1989–2017. Figure 2(a) plots the selected studies by year and publication type. The figure indicates that a substantial activity on field testing started in 2002. Since then, an average of 4.68 studies per year were published, with more papers published in the last 10 years. Most of the considered studies are conference papers (51/80), followed by journals (19/80) and few workshop papers (8/80) and book chapters (2/80).

Figure 2(b) details the main publication venues, reporting venues that hosted at least two studies. There is a considerable variety of publication venues, with 60 different venues for the 80 studies. It is worth to note the presence of venues like Transactions on Service Computing and International Conference on Web Information Systems and Technologies, with several studies on testing of service-oriented architectures, where testing in-the-field is of particular relevance.

2.4 Replicability of the Study

The outcome of our classification work as well as the list of all the 434 returned by the execution of the query string are made available for the interested researchers on the ACM Digital Library as supplemental online material of this manuscript.



(a) Field testing studies per year and venue type (b) Field testing studies by venue

Fig. 2. Field testing studies: quantitative results.

3 FIELD TESTING

This section introduces field testing. The analysis of the literature revealed no uniform and consistent way of referring to testing solutions in the field, thus in this section we define the terminology that we consistently use in the article. While in-house testing refers to activities in controlled environments specifically arranged to support the testing activities themselves, field testing refers to a range of activities closely related to the production environment that we characterize first, before introducing field testing.

Definition 1 (Production Environment). The production environment of an application is any environment where the application can be fully operational.

Production environments include hardware, software, such as system software, libraries, middleware, application-level software, and any other element that may affect the behavior of an application, such as sensors, input devices and network components. As an example to help clarify the following definitions, we could think of a provider responsible for an e-commerce platform FooZon: We consider the case that while developing a new extended feature, they need to perform an extensive testing across differing configurations, as well as differing customer profiles. The same application can be in fact deployed and used in multiple production environments, for instance an app FooZon can be installed in millions of different devices with different settings, or the platform can be accessed directly from its web application, again using different browsers and versions.

The production environment of an application is a dynamically evolving entity whose characteristics change at different speeds. For example, hardware components tend to remain the same (e.g., a component might be upgraded only after several years to improve the hardware equipment of a server), configurations change relatively rarely (e.g., a user may decide to change some settings to accommodate some emerging needs), while contextual elements may change quickly (e.g., the battery level and network connectivity may change quickly for mobile apps).

Since an application can be installed and executed in many production environments, testing activities must take such a variety and heterogeneity of environments into consideration. The notion of *field* refers to the many production environments relevant for a software application.

Definition 2 (The Field). The field of a software application is the set of all its (possible) production environments.

Field testing techniques address the challenge of validating the behavior of applications in the field, that is in all (or more practically in most) of its production environments, while considering the dynamic evolution of their characteristics. Figure 1 illustrates the main kinds of field testing, distinguishing between (right-side) testing activities performed in the field (aka in-vivo) and (left-side) activities performed in-house (aka in-vitro). Although in-house activities do not directly interact with the field, there are forms of testing that benefit from activities performed in the field.

Definition 3 (In-house/In-vitro Software Testing). In-house (in-vitro) software testing indicates any type of software testing activities performed in a testing environment completely separated from the production environment.

In-house software testing implies the presence of both the SUT (e.g., the considered example of the FooZon e-commerce platform) and a set of test cases that are executed against the SUT within the development environment (e.g., a user access, a user browsing different products, a user concluding a transaction, etc.). This survey considers only in-house testing activities influenced by information obtained *from the field*.

Definition 4 (Ex-vivo Software Testing). Ex-vivo software testing indicates any type of software testing performed in-house using information extracted from the field.

Ex-vivo testing is a specific type of in-house testing, which can be very useful for the testing of applications processing large amounts of structured data that are costly and/or difficult to build artificially. For example, instead of creating a series of accesses by different categories of customers trying to mimic many different operational contexts and client behaviors, the testers of FooZon could keep track of actual invocations coming from real transactions across different countries and relative to different types of products, and use these for more realistic and extensive testing of newly deployed versions. In our survey of literature, we found a few examples, as in the work by Morán el al. [74], where the authors employ data collected from actual user requests for the testing of MapReduce distributed data processing applications, thus overcoming the costs of building huge amount of data as those used in these applications. Another example is the work by Elbaum and Hardojo [34], where multiple techniques for enhancing an existing test suite by leveraging field data collected by profiling a web application under different strategies are assessed. Although ex-vivo testing does not imply running the test cases in the production environment, it is a relevant class of approaches in the scope of this survey, because they extensively use field data. Figure 1 represents the case of ex-vivo testing as the only kind of in-house testing activity relevant to this study.

Related to ex-vivo testing, there are a number of works that exploit failure/crash data from field executions for the generation of test cases that would help in reproducing the failures for in-house debugging (e.g., References [29, 50, 52, 88, 92]). Such works aim at generating test cases that recreate the failures observed in the field, guided by information about the failure collected from the field. The failure information from the field could be obtained by explicit instrumentation of the program before deployment for the purpose of capturing essential data (e.g., References [50, 52]). In other cases, crash data produced by the runtime environment (such as stack traces or core dumps) are used for the purpose of test generation (e.g., References [29, 88, 92]).

The test cases generated in this context are primarily used to recreate reported field failures for in-house debugging. Their scope is limited to helping developers understand and fix reported field failures, and eventually verify that the fix resolves the reported issue. They are mentioned here as related work as they make use of field data for test generation, however they are not included in our survey as they are focused on debugging rather than the process of field testing.

Definition 5 (Field/In-vivo Testing). Field (in-vivo) testing indicates any type of testing activities performed in the field.

Field testing activities can be executed *offline* or *online*:

Definition 6 (Offline Testing). Offline testing indicates field testing activities performed in the production environment on an instance of the SUT different from the one that is operational.

The software used in offline testing activities and the operational software may be distinguished in different ways: For example, with reference to the FooZon platform, the provider could opportunistically duplicate the components responsible for completing purchase transactions, and in any field testing execution involving a purchase replace the invocation to the actual component with the dummy duplication that will not really conclude any transaction, thus limiting the degree of intrusiveness of field tests on the operational software system, because no actual product is bought. Obtaining distinct instances of the SUT for off-line testing can be expensive, and may not guarantee perfect isolation of the testing process. For instance, a program can still interact with some environment elements, and test execution must be properly sandboxed to prevent side effects, as illustrated in the work by Murphy et al. [75], who proposed an approach to duplicate the field environment by forking the process under test.

Definition 7 (Online Testing). Online testing indicates field testing activities performed in the production environment on the actual software system.

Online testing pushes forward the concept of field testing by directly testing the operational software system. Online testing might be preferable to offline testing in terms of the representativeness of the test outcome, but online testing can be extremely complex, since the testing activity might easily interfere with the normal activity of the software under test. Considering again FooZon, online field testing may entail launching some browsing executions pretending to be a customer and placing actual transactions, which are issued for testing purposes side by side with visits and transactions performed by real customers. In addition to possibly sustaining the real costs of purchases concluded while testing and their expeditions, this practice may also negatively impact customers experience, for example competing with them for the purchase of products of limited availability, or slowing down actual deliveries to customers.

Notwithstanding the possible side effects, online testing is nowadays increasingly performed in practice by some providers, of course when the SUT has no safety-critical aspects. For example, in NetFlix the concept of Chaos engineering for online testing the robustness of their cloud services has been established a decade ago and still continues to be expanded [9].

In the next section we introduce the research questions addressed in the scope of this survey to study ex-vivo, offline, and online testing approaches.

4 RESEARCH QUESTIONS

The *goal* of the survey is to characterize the existing research on field testing, in terms of *objectives* of field testing activities and *approaches* to achieve them. We want also to understand the practical implications of the proposed approaches, in terms of required field *resources* and overall *management* of field testing, as opposed to management of traditional in-lab testing. Correspondingly, we designed two research questions focused on the "how" (RQ1) and "what" (RQ2) dimensions, which cover respectively approaches and objectives. Furthermore, with RQ3 and RQ4 we investigate the resources and management activities required for field testing. Overall, this survey addresses four main research questions, all characterized by several dimensions.

RQ1 - How is software tested in the field? This research question addresses the type of testing activities performed in the field. We detail the general question in two sub research questions:

RQ1.1 - What are the approaches, fault types, test case generation and platforms used in field testing?

RQ1.2 - What are the source, strategy, triggers, resources and oracles used in field tests?

To answer this research question, we classify the approaches based on their category (*ex-vivo*, *offline*, *online*), the type of addressed faults (*functional*, *non-functional*), the strategy used to *generate* test cases, and the developed support platforms, and provide an organized map of field testing solutions (Section 5). We study *where* field test cases are generated (which may be a different location from where they are executed), the events that may *trigger* their execution, the *resources* that are typically considered in the field testing process, and the used *oracles* (Section 6).

RQ2 - What is tested in the field? This research question addresses the software elements that are tested in the field. We consider the *test target*, for instance new or modified features, the *granularity* of the software elements under test, for instance single components or the system as a whole, and the *type of tested applications*, for instance mobile or server applications (Section 7).

RQ3 - What is required to execute tests in the field? This research question addresses the features that field testing solutions require to execute the test cases in the field. We consider four main dimensions: *monitoring*, which includes the techniques used to extract information about the behavior of the SUT; *isolation*, which includes mechanisms to guarantee that the execution of the field tests does not interfere—or has negligible interference with—the regular operation of the tested software; *privacy* and *security*, which include solutions to guarantee the privacy and the security of the users despite the activity performed in field testing (Section 8).

RQ4 - How is field testing managed? This research question addresses management and control aspects of field testing, also in view of possible evolution of the software under test. The overall problem of managing a testing session in the field is that it should have minimum impact on the end users and on the normal production activities. Moreover, key decisions to be made in the field include which tests to select for field execution and how to prioritize them for execution, under the assumption that there might not be enough resources to run all the available tests. Hence, we identify three dimensions: *test selection* to select the test cases to be executed in the field to validate changes; *test prioritization* to sort the test cases to be executed in the field to validate changes; and *test governance* to control the testing process and the involved stakeholders (Section 9).

5 RQ1.1: APPROACHES, FAULT TYPES, TEST CASE GENERATION AND PLATFORMS

In this section, we analyze field testing techniques by considering the *field testing approach* and the *test case generation strategy* dimensions of the classification. We distinguish between approaches that address functional and non-functional faults (Table 1) and classify approaches based on the target platforms (frameworks and architectures) (Table 2).

The studies are not evenly distributed with respect to the *testing approaches*: We found few ex-vivo and offline field testing techniques, and many online field testing techniques. This indicates a strong interest toward techniques that test exactly the operational application.

The nature of the *requirements* that are tested is not evenly distributed within each testing approach. Most ex-vivo and offline field testing approaches focus on functional requirements. Only two approaches address offline testing of security requirements to assess the security of software systems in the operational environment as early as possible [24, 25]. Online testing approaches address both functional and non-functional requirements.

Concerning the problem of *test case generation*, in field testing a test case has a broader scope than just the test input data. The actual novel challenges in generating field tests descend from identifying and reproducing with each test case the relevant interactions with the field, whereas

Table 1. Testing Techniques

Testing approach		Test Generation Strategy			
		Specification-based	*Structure-Based*	*Fault-Based*	*Pre-existing*
ex-vivo	*functional*	*Mutation of Field Executions* [28, 74, 78, 79] *Test Suite Adaptation* [38, 47, 48]	*Profile Data* [34]		*Field Triggers* [72]
offline	*functional*	*IO Data Pattern* [81] *Metamorphic Relations* [10, 76]			*Built-in Tests* [54, 55, 75, 93, 94, 99] *Test planning and management* [42, 43, 77] *Adaptation and Reconfiguration* [62, 64]
	non-functional	*Security Specifications* [24, 25]			
online	*functional*	*Choreographies and Service-based specifications* [2, 5, 6, 12, 22, 98] *Finite-State Models* [18, 20, 33, 71, 95] *Metamorphic Relations* [21] *Graph grammars* [83]	*Event Interface* [101]	*Fault Injection* [102]	*Test planning and management* [1, 14, 27, 42, 43, 59, 60] *Adaptation and Reconfiguration* [32, 44, 53, 62, 64] *Isolation* [17]
	non-functional	*Stochastic Models of User Behavior* [82, 89] *Security Specifications* [12, 13, 26, 46] *Usability Models* [69] *Δ-grammars for QoS* [83] Timed-automata [71, 95]		*Fault Injection* [3, 102] *Operational Profile* [73]	*Adaptation and Reconfiguration* [32, 67, 70]

Table 2. Platforms for Field Testing

Offline Testing Platforms		**Online Testing Platforms**	
Evolution [58, 61, 63, 66] *Shadow Instances for V&V* [40, 45]	*SOA and Component-Based Testing* [8, 16, 81, 103, 104, 105]	*Built-In and Pre-Existing Test Cases* [30, 31, 41, 51, 81, 100] *SOA Online Testing* [80]	*Evolution* [23, 37, 58, 61, 63] *Distributed Quality Assurance* [87]

a priori we do not expect that new, ad-hoc techniques need to be specified for generating the test inputs data. We cluster techniques in four categories [85] depending on the information used to generate the test cases, as is also done for in-house testing: (i) *Specification-based* techniques derive test cases from formal or informal requirements specification; (ii) *Structure-based* techniques use structural information, mostly the code structure, to derive test cases; (iii) *Fault-based* techniques use models of potential faults (*fault models*) to derive test cases that address the faults represented in the fault model; and (iv) techniques working with *pre-existing* test cases exploit already available test cases. We observe that most commonly black-box techniques are used. Namely either test cases are generated from specifications, to suitably cover certain behaviors, or strategies are defined to execute test cases that are already available, for instance from field monitoring. Only few approaches derive test cases from structural information and fault-models.

The available platforms, as shown in Table 2, offer a range of solutions for both offline and online testing targeting several environments (e.g., service and component-based systems) and scenarios (e.g., continuous quality assurance and evolution).

The classification in Tables 1 and 2 provides a roadmap to researchers, who can easily understand the positioning of the individual studies with respect to the existing literature along the identified dimensions (testing approach, test generation strategy) and along the respective subdimensions. It is also potentially useful to practitioners, when they face a specific field testing problem. Thanks to the presented classification, they can find relevant research papers and tools that address the kind of field testing approach they want to implement (ex-vivo, offline, and online) and the kind of test generation strategy they intend to adopt (structural, fault oriented or pre-existing tests). *The detailed descriptions of the individual approaches that appear in Tables 1 and 2 are available in a report that is part of the online supplemental material associated with the article.*

5.1 RQ1.1: Findings

We conclude this section summarizing the key findings with respect to the type of addressed faults, the test case generation strategies, and the platforms proposed so far:

- *Approaches privilege functional versus non-functional faults, which are still under-investigated:* The majority of approaches address functional faults. The few approaches that address efficiency, security, reliability and usability, shed some initial light on a largely unexplored domain that calls for non-intrusive testing techniques to properly address non-functional properties.
- *Quality of service is a relatively well-studied quality attribute among non-functional aspects:* Many of the approaches that deal with non-functional properties address the relevant problem of predicting the QoS of applications executed in different and heterogenous production environments.
- *Specification-based test case generation approaches are by far the most studied approaches:* Many approaches rely on specifications to generate field test cases, leaving open the hard problem of generating test cases in absence of specifications, as in the many cases of systems that evolve beyond the initial specifications to adapt to emerging execution conditions and configurations.
- *Automation is still limited:* Many approaches rely on relevant human contribution and already available test cases, and automation of field testing is still limited.

6 RQ1.2: Source, Strategy, Triggers, Resources, and Oracles

In this section, we discuss where field test cases are generated (Section 6.1), how field test cases are executed and triggered (Section 6.2), what resources field test cases require (Section 6.3), and which oracles validate the result of field test execution (Section 6.4).

6.1 Where Field Test Cases Are Generated

Field test cases may be generated and executed at different times and locations: in-house, in-house with field data, and in the field. Field test cases generated *in-house* are produced during development. Field test cases generated *in-house with field data* are produced during development by exploiting information observed in the field. Test cases generated *in-house* can be executed either in the development environment (ex-vivo testing) or in the production environment (in-vivo testing). Test cases generated *in-the-field* are generated in the production environment.

Table 3. Place *Where* Tests Are Generated

Place	Number of papers	%
In-house	32	44%
In-house with field data	9	12%
In-the-field	32	44%

Table 3 shows the distribution of the different approaches with respect to environments for generating test cases. Relatively few approaches generate test cases in-house with field data (12%), most approaches generate test cases either in-house or in-the-field with an even distribution between the two sets (44% each). Test cases generated *in-house* address scenarios known to be possibly field-relevant but not completely available at design time yet, such as configurations that depend on dynamic information, for instance dynamically discovered services. Test cases generated *in-the-field* address scenarios that emerge and can be identified only in the field and cannot be identified in early development phases. Generating test cases in-house is easier than in-the-field but produces test cases with a scope limited to at least partially predictable scenarios, while test cases generated in-the-field may address a wider set of scenarios.

6.2 Test Strategy and Triggers

Testing strategies and triggers refer to the way approaches identify critical events that activate field test cases. Testing *strategies* are *proactive* if they primarily aim to anticipate failures that could occur in the production deployment, *reactive* if they primarily aim to manage the effect of field failures after their occurrence. We refer to the events that lead to the activation of field test cases as *triggers*. A trigger is any kind of event, scenario, or configuration whose occurrence leads to the execution of some field test cases.

Most studies of field testing strategies propose proactive strategies: 63 papers, that is 86% of the papers that deal with test strategies, propose proactive strategies; 5 papers, 7%, propose reactive strategies, that is, activate testing sessions *in-the-field* as a consequence of observed failures; 5 papers, 7%, support both strategies. For instance, Kawano et al.'s approach [51] proactively activates test cases when modules change, and reactively responds to failures.

Figure 3 classifies the strategies according to the triggers they react to. The taxonomy identifies two main kinds of triggers, *IT Operation* and *Evolution*. IT Operation triggers are events that derive from some either internal or external operations of the system. Evolution triggers are events that derive from some dynamic transformation of the system or its components. Triggers are not exclusive, in fact some approaches can react to multiple triggers.

IT Operation triggers may be periodic or asynchronous events. While few studies focus on periodic events, the majority of approaches that react to IT operation triggers refer to asynchronous events. Some approaches react to asynchronous events internal to the SUT, related to custom events, unchecked exceptions, idle states, data and transmissions. Other approaches react to external triggers, related to test sessions, system policies, or external functionalities. Triggers related to test sessions derive from inputs by a client or another system/module, a QA team member, or the runtime infrastructure, and decouple the decision-making aspect from the technical field testing solution. Triggers-related system policies depend on explicit decision policies that can be defined by ether the service integrators or testers, or can be based on data observed in the field. Triggers related to external functionalities depend on the activation or usage of particularly relevant functionalities, and are defined either statically before or dynamically at runtime.

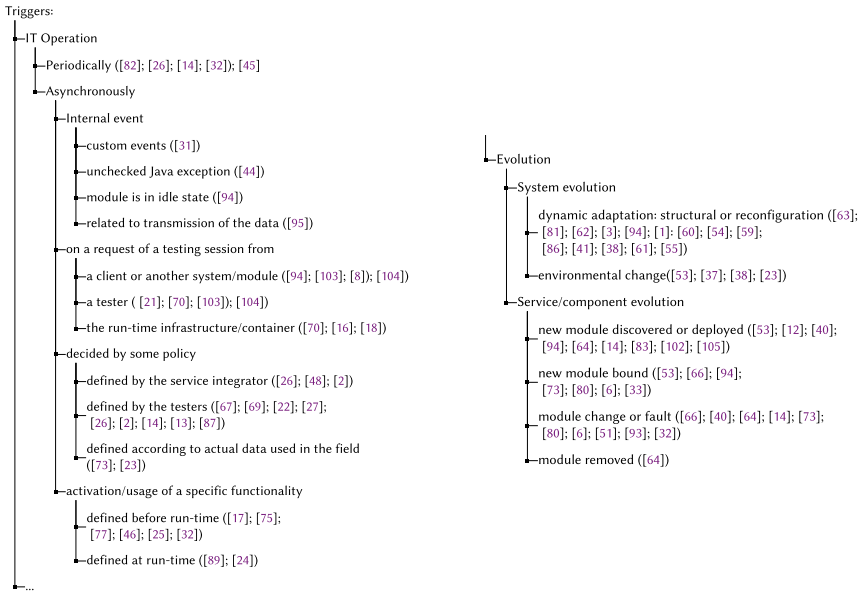


Fig. 3. Test triggers used to run tests in the field.

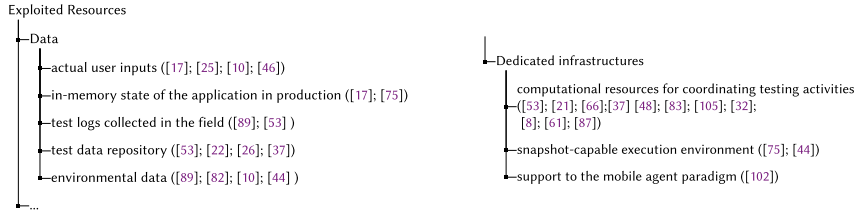


Fig. 4. Exploited resources.

Evolution triggers react to the evolution of either the whole SUT or some components. System evolution triggers react to either dynamic reconfigurations or environmental changes, component evolution triggers react to discovering, binding, failing or removing components.

6.3 Field Resources

In-vivo testing approaches require the availability of different *resources* in the field. In this section, we overview both the required field data and the infrastructures dedicated to field testing. We discuss the resources required to isolate executions of field tests in Section 8.2.

Figure 4 shows both the kinds of field data and dedicated infrastructures that different approaches require. Several approaches rely on the data obtained from production. Bobba et al. [17] exploit *user inputs* to detect failures, Dai et al. [25] exploit *user inputs* to detect security vulnerabilities introduced by changes in the configurations. Bell et al. [10] mutate user inputs and observed outputs, leveraging metamorphic testing or weak-mutation strategies, to produce new test cases, Hui et al. [46] mutate inputs and outputs to reveal security vulnerabilities.

Other approaches rely on the *in-memory state* of the application in production. Bobba et al. [17] and Murphy et al. [75] exploit the in-memory state to discover faults hard to reveal in-house. Some works exploit data from the *logs* or from the verdicts collected in the field while executing in-vivo testing sessions. Sammodi et al. [89] use such information to predict adaptations, while

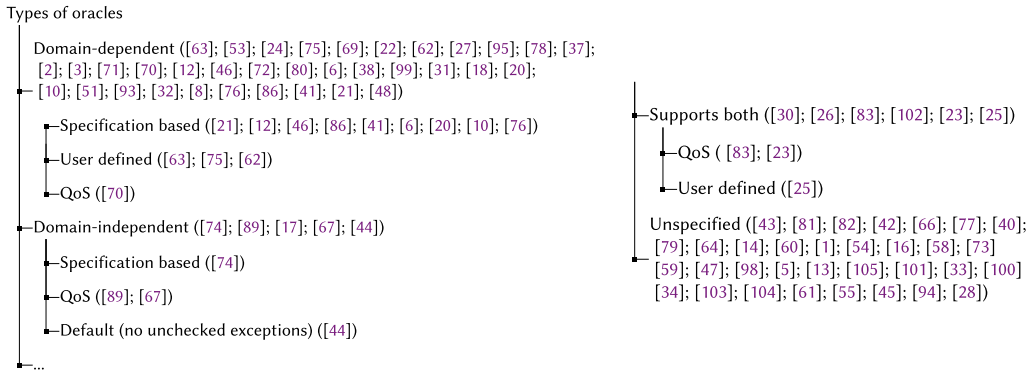


Fig. 5. Types of oracles.

King et al. [53] detect symptoms of undesirable SUT states. Many field testing approaches require specific data, and rely on dedicated *test data repositories* to store regression test cases [22], authentication/authorization cookies [26], or more generally mutable test artefacts so as to keep them consistent with the current operating conditions [37]. Some approaches take advantage of information on both the *environment* and the execution context. For instance, Gu et al. [44] infer useful information for testing from the state of the hosting virtual machine.

Field testing approaches may require additional *infrastructures* that are not part of the SUT to be available *in-vivo*. A common case is the request for *computational resources for coordinating* the testing activities, necessary when multiple components are involved in field testing. While approaches based on replicas use either *snapshot-capable execution environments* to simplify replica management [44, 75] or *agent-based paradigm* to migrate components between hosts [102].

6.4 Field Oracles

Field testing approaches rely on different kinds of test *oracle* to decide the test outcome. *Domain-dependent* oracles require information about the SUT application domain, for instance oracles that assert the results expected for some operations; *Domain-independent* oracles, such as oracles that assert the availability of the SUT, do not require the specific knowledge of the SUT's application domain. Figure 5 classifies the approaches depending on the test oracles as *domain-dependent*, *domain-independent*, and hybrid, if they *support both* types of oracles.

Many studies (34 papers ≈ 43%) do not present specific oracles. The majority of studies that propose some oracle (76%) rely on domain-dependent oracles, 5 approaches rely on domain-independent oracles, 6 approaches rely on a combination of both types of oracles. The effort on oracles indicates that many field failures do not cause crashes and require some knowledge about the SUT to be detected. This is not a surprise, since in-vivo testing usually addresses stable applications, and is designed to reveal problems related to corner cases and infrequent scenarios.

Most approaches that consider some form of oracle do not explicitly discuss the techniques used to implement the oracles. Only 20 of 46 approaches (43%) explicitly describe the proposed oracles. The majority of approaches that explicitly define an oracle use some form of specification-based oracles: component specifications [12], SUT models or specifications [6], and BPEL specifications [20]. Several approaches refer to metamorphic relations [10, 21, 46, 74, 76]. Some approaches rely on user-defined oracles [25, 62, 63].

Some domain-independent oracles rely on QoS attributes of the SUT, such as general performance metrics, like response time [23, 70, 89], or execution duration and availability [83]. Few studies exploit the default oracle, that is, the detection of crashes or unchecked exceptions [44].

6.5 RQ1.2: Findings

We conclude this section by summarizing the key characteristics of field testing approaches with respect to the source (where test cases are generated), strategies, triggers, resources, and oracles.

- *Sources of Field Test Cases:*
  Approaches for field test cases are evenly distributed between in-house and in-the-field generation: While several approaches investigate the opportunistic generation of test cases in the field to address unforeseen issues, test cases generated in-house are often sufficient to address field issues. Indeed, complex strategies that operate in the field are not always required. Simultaneously, improving the opportunistic and dynamic generation of field test cases is still an objective.
  Ex-vivo testing strategies are still largely under-explored. Only few approaches take advantage of data from the field to generate effective field test cases, and execute them in the field, leaving a large space of opportunities for further study.
- *Strategies and Triggers:*
  Most field testing approaches aim to predict failures, thus confirming the intuition that the main goal of *in-vivo* testing is to prevent failures to occur.
  Field testing activities are triggered both by events in the SUT and in the environment, and by evolutions of the SUT or its components: Only few approaches periodically activate testing sessions, while most approaches rely on asynchronous triggers related to the SUT, such as structural changes and reconfigurations, and the environment, such as new configurations and components.
- *Resources:*
  In-vivo testing approaches heavily rely on data from the final production environment: Field data are important sources of information for field testing to identify new scenarios and corner-cases. Field data include user inputs, state information, logs, and environmental data.
  In-vivo testing often demands additional engineering not required for the SUT: Gathering data from the field and coordinating field testing activities require non-trivial (hardware, virtual and software) infrastructures. Designing these infrastructures can be challenging, due to their impact on the complexity of the SUT, and the possible introduction of threats to safety and security that must be carefully addressed and compensated by the benefit of running field testing.
  Many approaches do not explicitly mention the resources needed in the testing sessions: The additional resources required by field testing are not always explicitly discussed as part of the approaches, despite the required extra-cost and the extra-engineering effort.
- *Oracles*
  Specification-based oracles are the most common field testing oracles: Field testing approaches often rely on specification-based oracles, with metamorphic relations frequently used both as oracles and as a support to generate new test cases.
  The oracle problem is overlooked: In many cases the oracle either is not specified or the default one is used, resulting in approaches that might miss relevant failures due to lack of proper oracles.

7 RQ2: TEST TARGET, GRANULARITY AND TYPE OF TESTED APPLICATIONS

In this section, we discuss the targets of field testing (Section 7.1), the granularity of the software tested in the field (Section 7.2), and the type of applications considered for field testing (Section 7.3).

Table 4. Targets of Testing Approaches

Target	Number of approaches	%
New feature	24	35%
Regression	37	54%
Changed feature	28	41%
Changed environment	19	28%

Table 5. Granularity of Testing Approaches

Granularity	Number of papers	%
Unit	45	57%
Subsystem	29	37%
System	25	32%
System of Systems	2	3%

7.1 Target Features

Field testing can be designed to address different target features:

- *New features*: the feature is either new or tested without using information about past versions.
- *Regression issues*: the feature is tested after a change that is expected to have no effects on it.
- *Changed feature*: the feature is tested after a change that is known to affect its behavior.
- *Changed environment*: the feature is tested after detecting a change in the environment.

Table 4 shows the distribution of the different approaches with respect to the target features. It is worth noting that some approaches address more than one type of targets.

Most approaches deal with regression testing (37 papers). In-vivo regression testing is used especially for software systems that can be dynamically reconfigured or adapted while running in the production environment, such as autonomic computing systems [54], and component-based systems [63]. Regression testing is also considered in ex-vivo approaches, as a way to obtain additional test cases that can reveal the side effects of changes [72].

Field testing has been also significantly employed to test the impact of environment evolution. In fact, it is hard to exercise in-house every possible environment and every possible configuration. Leveraging the natural diversity of environments available in the field is a clear strength of field testing.

When a new feature is released or an existing feature is changed, the validation activity cannot always be completed in-house, especially if the behavioral space of the SUT is large. Field testing has been exploited to continue validation activities in the field and discover the missed faults.

Although revealing regression problems has attracted more attention than other possible targets, all the four scenarios have been significantly investigated in the domain of field testing.

7.2 Granularity of the Tested Elements

Granularity refers to the granularity level of the tested elements: unit/component/service, integration/subsystem, system, or **system of systems (SoS).** Table 5 shows the distribution of the different approaches with respect to the addressed granularity level. Indeed, the majority of the

Table 6. Approaches per Application Type

Category	Number of papers	%
Remote	59	74%
Embedded	10	13%
Desktop	11	14%
Mobile	1	1%

studies consider unit, integration, and system testing, with most approaches focusing on unit level. In many cases, field testing approaches target multiple levels. Our analysis indicates the testing of System of Systems as a largely unexplored area. Given the growing complexity, size and degree of interoperability of modern software systems, such a level deserves greater attention in the future.

7.3 Type of Tested Applications

The type of application directly influences field testing techniques, since it impacts on the core mechanisms, namely runtime test execution, isolation, and monitoring. Current field testing approaches address four main classes of applications: *Desktop* applications, which run on desktop or laptop devices; *Mobile* applications, which run on mobile devices, such as smartphones, tablets, smartwatches; *Remote* applications, which run on servers, usually accessed via client applications, installed on desktop or mobile devices; and *Embedded* applications, which run on dedicated components with time and robustness constraints, and that are not as frequently updated as other types of applications.

Table 6 shows the distribution of the different approaches with respect to the type of addressed application. Most field testing techniques address remote applications, whose many resources facilitate the design of key features, such as isolation (often obtained by replicating components) and monitoring (ofter provided with little interference on the running systems). This is especially true for cloud infrastructures that provide virtually unlimited computing resources.

Field testing approaches that target embedded applications consider interactions with hardware and environment, and focus primarily on ex-vivo testing [28, 78, 79] that can be safely performed in-house. Only few approaches deal with online testing for systems with strong fault tolerance and assurance requirements [3, 16, 40, 51, 95, 100].

Desktop applications receive little attention, probably due to the relatively low popularity nowadays. We found only one approach designed for mobile applications. The limitations imposed by mobile devices (limited computational resources) and mobile operating systems (security constraints) are probably quite challenging for field testing technology.

7.4 RQ2: Findings

We conclude this section summarizing the key characteristics of field testing approaches with respect to the target features, the granularity, and the type of the tested elements.

- *Target Features:*
  Field testing addressed a variety of test targets, with a focus on the presence of unexpected side effects as consequence of changes, and on new and changed features, and environment changes.
- *Granularity of Tested Elements:*
  Field testing is applied to all levels: units (functions, components, services), integration, and system. Indeed, field testing is a general solution that can address elements of different size and complexity.

SoSs deserve more attention: SoSs are systems composed of multiple independent systems that cooperate opportunistically. Although so far they received little attention, they are complex systems that require field validation techniques to be properly addressed.

- *Type of Tested Applications:*
  Most approaches apply to server applications that provide enough resources to easily address some of the key challenges of in-vivo testing.
  Mobile applications are challenging: Mobile applications can be deployed on a huge diversity of devices, and can interact with the environment in a rich way thanks to the many sensors they can be connected to. It is thus an extremely interesting context for field testing. However, so far, field testing is still substantially unexplored. This is probably due to the constraints imposed by the mobile computing environment, such as the security and resource constraints, that make the deployment of field testing difficult. We expect more work in this domain in the future.

8 RQ3: Monitoring, Isolation, Privacy, and Security

In this section, we discuss how field testing approaches monitor the SUT (Section 8.1), isolate tests in the field (Section 8.2), and address privacy and security in field testing (Section 8.3).

8.1 Monitoring

Monitoring is the process of dynamically gathering, interpreting, and elaborating data about the execution of the SUT. Monitoring is extremely important in field testing, as it captures data about events and states of both the SUT and the environment. Such data are needed to trigger the testing process, generate and select the test cases and identify the testing activities.

We distinguish direct and indirect monitoring, based on the source of information, that is, who produces the information. Monitoring is *direct* if the monitored information comes directly from the SUT, *indirect* if the monitored information comes from the software, physical or human environment where the SUT operates, for instance OS resources consumption, data read by sensors or data about user interactions with the system. We discuss *what* is monitored, that is, the information the monitoring facilities gather to support field testing, and *how* monitoring is implemented, that is, what techniques are used. The activities for *gathering* information include:

- *logging*: the process of recording textual and/or numerical information about *events of interest*,
- *tracing*: the process of recording information about the *control flow* of a SUT during its execution.

Logging and tracing differ in their goal, even when implemented with similar techniques, for instance by instrumentation: Tracing records the execution flow of the SUT execution without referring to specific classes of events of interest, while logging focuses on the events of interest, for instance, recording errors or failures. In the following, we discuss the monitoring solutions in field testing, by focusing on (1) what is monitored and (2) how software is monitored.

Figure 6 groups field testing approaches according the targets of the monitoring activities, that is, the information of interest. Approaches that monitor different kinds of information are associated with more than one branch in the tree in the figure. We distinguish *(i)* approaches that monitor the *state* of the SUT itself, the system in which the SUT is executed, or the environment with which the SUT interacts, which entails reading the values of the variables of interest; from *(ii)* approaches that monitor *events of interest*, that is, events that cause the state to change, for instance, an action of a user that caused a reconfiguration or some method calls. Our survey indicates that 55 of 80 (69%) studies explicitly specify *what* is monitored to support the testing process.

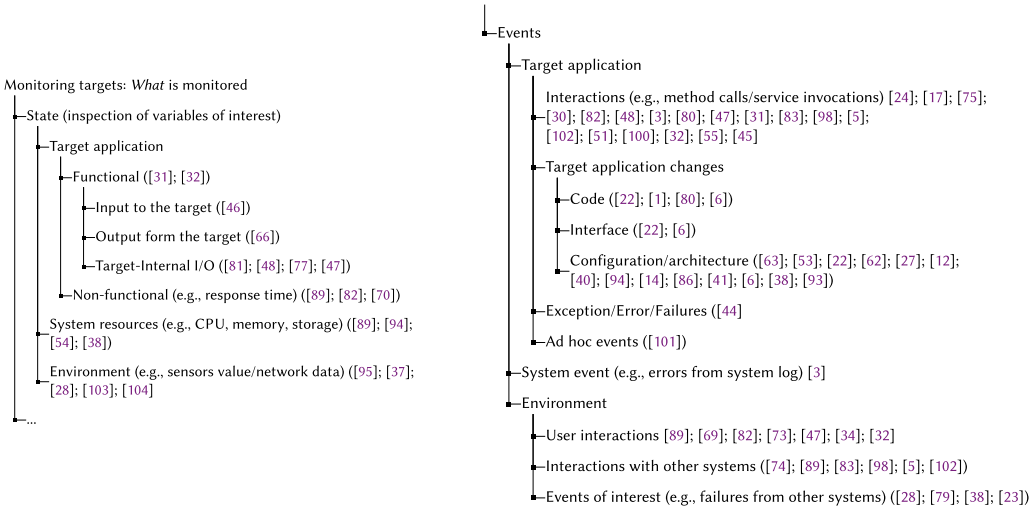


Fig. 6. Field testing approaches by monitoring targets.

Many field testing approaches monitor the *state of the target*, namely the values of variables of interest. In several studies, the monitoring solution intercepts *functional* values of the variables of interest, namely the input/output exchanged to/from the target and within the target's modules. For instance, Hui et al.'s approach [46] detects integer overflows by online metamorphic testing. The approach monitors *inputs of insecure integer data* along with sensitive code paths to detect untrusted sources of integer values with their paths to security sensitive sinks. The approach uses the information to trigger testing, which exploits metamorphic relations to test the same path with untrusted values. Lee et al.'s approach [66] proposes an architecture for field testing of embedded systems that extends the Simplex architecture, to allow components to be upgraded and tested online. The approach compares the output of the component under test to the output of the component that is replaced in the Simplex configuration, in order for the system to benefit from the new component while still assuring a correct computation.

In many cases, field testing accesses the Internal I/O operations of the SUT modules. Hummer et al.'s approach [47] focuses on integration testing of dynamic service compositions, in which the data flowing within the BPEL composition is observed to generate test cases. Murphy et al.'s approach [77] monitors the values of variables in the scope of the function under test to understand if the application is traversing a previously unseen state and need to be tested.

Some approaches monitor *non-functional* attributes. Ma et al.'s approach monitors the system response time to perform adaptive performance testing of web services [70].

Other approaches monitor system-level information about *resource utilization* or about the *environment*. King et al.'s approach monitors the state of managed resources in autonomic computing systems to trigger self-testing routines [54]. De Olivera Neves et al.'s approach monitors the environment with sensors to trigger environment-dependent field test cases [28].

Some approaches monitor *events* at the level of the *target application*. In many cases, the events are about the *interaction within the application*, such as method calls or service invocations. In other cases, the events are about *changes that may occur in the target application* (e.g., module/service upgrades, interface changes and reconfigurations) and tests assess the impact of these changes.

Other approaches monitor *exceptions/error/failures* (e.g., unchecked Java exception [44]) or domain-specific *ad hoc* events (e.g., events specifically defined for coverage assessment and

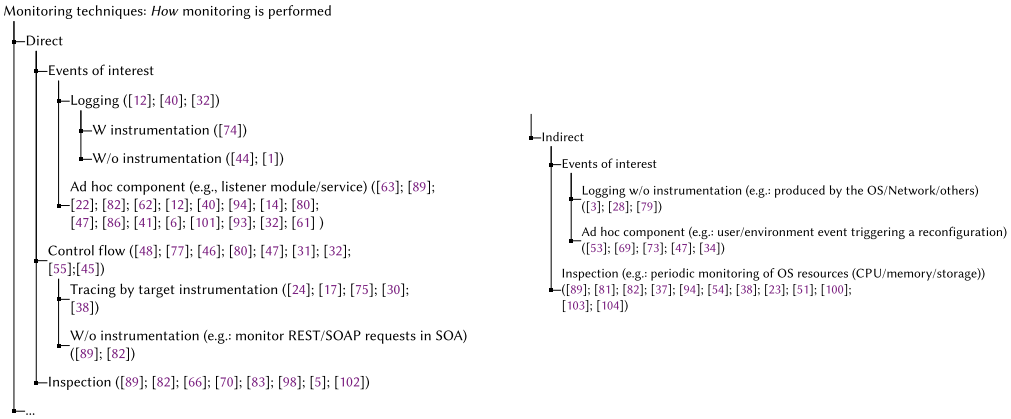


Fig. 7. Field testing approaches by techniques.

published in the event interface [101]). Approaches can also exploit *system events*, such as data present in the logs, to assess the expected versus observed behavior during testing [3]. Some approaches monitor interactions of the target application with the external *environment*, by capturing *interactions* with *users* or *other applications/services* such as in the case of service compositions.

Figure 7 groups field testing approaches according to the technique adopted to monitor the SUT, that is, *how* monitoring is implemented. Approaches that monitor different kinds of information are associated with more than one branch of the tree in the figure.

Our survey indicates that 53 of 80 (66%) of the studies explicitly indicate the monitoring technique, that is, *how* monitoring is performed (direct vs. indirect).

Many approaches implement direct monitoring by *logging* runtime information either with or without instrumenting the SUT, in the latter case by exploiting information natively logged by the target application. Few approaches rely on ad-hoc components designed to capture a specific class of events. For example, Cooray et al. rely on the ODE-BPEL extension that provides the BPEL event listener API to monitor the Web service process execution [22].

Some approaches monitor the system by tracing the *control flow* of the execution, either with or without (static or dynamic) instrumentation. Other approaches periodically *inspect* SUT attributes.

Approaches that implement *indirect monitoring* are driven by information from the system and the environment. Some approaches access *logged information*, such as operating systems, network, and sensors logs [3, 28]. Other approaches propose *ad hoc components* for monitoring users' or environment's events that trigger reconfiguration [53, 69]. Yet other approaches rely on periodic inspection of attributes of the system and the environment, such as system resource consumption [54] and network data [51, 100].

8.2 Isolation

Field testing should not interfere with normal operations nor produce undesired side effects. To prevent side effects on the execution flow of the SUT, field testing approaches either execute field tests in sand-boxed environments or do a roll-back before restarting normal execution. Field testing approaches are isolated at different levels. The *isolation level* of a field test is the computational unit that is subjected to isolation during field testing, and that can be safely field tested with warrantied no side effects on the running system. Depending on the granularity of field testing, which we discussed in Section 7.2, the isolation level may scale from small computational units, such as classes or functions, to large units, up to the entire SUT.

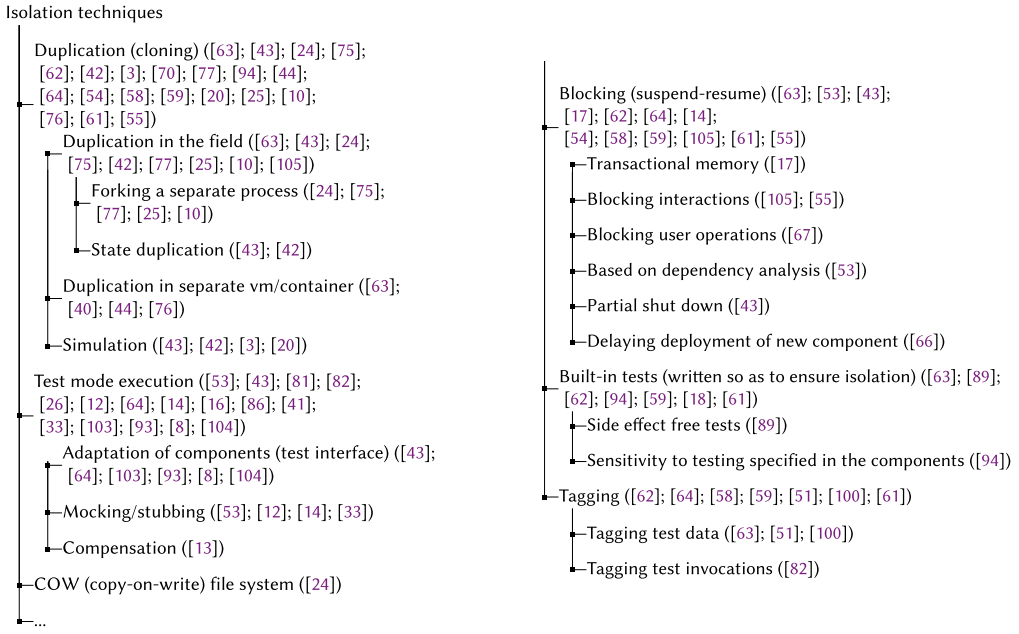


Fig. 8. Isolation techniques.

Many approaches do not discuss the isolation problem, and do not explicitly propose solutions. Isolation is not a problem for either *ex-vivo* approaches or *in-vivo* approaches that simply compare the behavior of the SUT observed in the field to the expected one without interfering [30].

Many approaches that target service-oriented applications either assume side-effect-free SUTs or suitable *compensation mechanisms* [13], that is, they assume that side effects can be either rolled back or compensated (e.g., by paying proper testing fees) when services are executed for testing purposes. In-vivo approaches that assume compensation mechanisms for allowing testers to (partially) ignore the side effects of in-vivo testing require careful engineering to avoid such compensation mechanisms to be abused or used beyond reasonable limits.

Some approaches address the isolation problem by assuming that test cases are side effects free by design [89]. The difficulty of designing field test cases with no side effects depends on the test granularity: It may be not too difficult at small granularity levels, but it becomes very difficult at high granularity levels.

Figure 8 summarizes the isolation mechanisms proposed for field testing. The most polular mechanism is *duplication*, also called *cloning*, that implements isolation by executing the field tests after duplicating the execution state, hence ensuring no interference with the execution in the production environment. Some approaches clone the execution state in the same execution space of the production environment (*duplication in the field*) by (i) *forking* a separate process devoted to in-vivo testing, (ii) *cloning the objects* involved in testing, or (iii) deploying redundant instances in the field for testing purposes (*state duplication*).

Other approaches separate in-vivo testing from the production processes, by either executing the field test cases in a *separated virtual machine* that duplicates the runtime environment or reproducing the main process in a *simulator*, possibly based on information gathered from the main execution by means of probes.

Another extensively used isolation mechanism is based on specific *test execution modes* that differentiate the execution in testing versus normal operational mode. The testing mode ensures

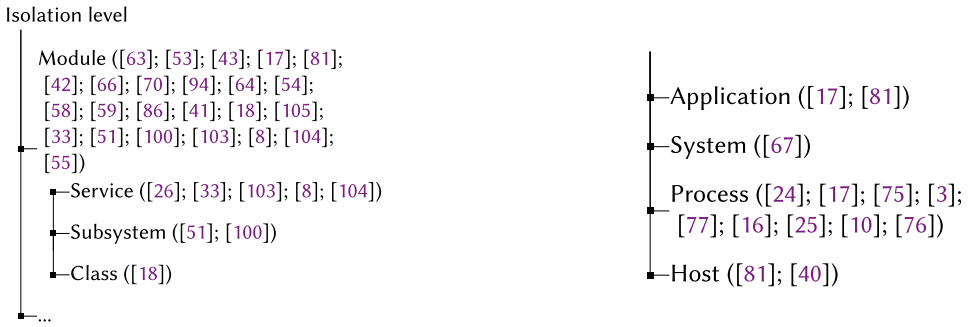


Fig. 9. Granularity of the computational unit being isolated during field testing.

that test cases do not affect the normal execution state. Test modes are implemented by (i) *adapting the behavior of the components*, for instance by using a test interface that in-vivo test cases use instead of the production interfaces; (ii) using *stubs and mocks*; or (iii) activating mechanisms that *compensate* the effect of test execution. All these variants assume that components are designed and developed for testability, with a test execution mode that prevents side effects.

A less investigated isolation mechanism is the usage of copy-on-write file systems [24], whose effectiveness is limited to side effects that leave a persistent trace in the file system.

Some approaches isolate field testing with *blocking* mechanisms that block the execution of components with potentially undesirable side effects for the whole duration of in-vivo testing. Field testing approaches implement blocking in various ways. A clean and elegant solution exploits *transactional memory*: In-vivo test cases are executed within a transaction that is rolled back when returning to normal execution. Variants of this solution include blocking either the *interactions* between components or *user operations* that may interfere with the execution process, identified with *dependency analysis*. Another way to implement blocking consists of *shutting down* all components that could interfere with the main process during in-vivo testing, to inhibit side effects.

Other approaches delegate isolation to the design of test cases (*built-in tests*). Writing *side-effect-free* tests is not a straightforward solution, highly dependent on the skills of testers, who are in charge of defining proper tests for in-vivo execution. Other approaches delegate isolation to the design of the components, by requiring the components of the system to declare their sensitivity to testing, in terms of side effects that may depend on executing test cases in the field. It becomes then a responsibility of the test cases to check that the components have an adequately low sensitivity to testing.

Few approaches implement isolation by *tagging* the information generated during in-vivo testing, so that it can be distinguished and handled separately from the information originated by normal execution. It is possible to tag either the generated *data* or the performed *invocations*.

Few approaches define explicit *isolation policies*. Lahami et al. [63] propose multiple policies, and assume that *developers choose* among the alternatives (a subset of those in Figure 8) once and for all, before deploying the test suite.

Gonzalez-Sanchez et al. [43] propose to declare policies in the components under test *based on the level of testability*, and configure specific isolation mechanisms based on the possible side effects declared in the components under test. Lahami et al. [58] define test cases *optimized for isolation*, by choosing the best isolation technique among the available ones, depending on component-system interactions.

Most isolation techniques work at *module* granularity level: *service*, *subsystem*, and *class*, as shown in Figure 9. Indeed, many of the techniques that exploit isolation strategies based on du-

plication, test mode, built-in tests, blocking, and tagging operate at module level. Isolation at the *process* level is also quite common, while *application*, *system* and *host* isolation levels are less frequent and often more challenging than isolation at low granularity levels.

8.3 Privacy and Security

Privacy and security issues are still largely unaddressed. Only 8 studies of 80 (10%) address such aspects. A common solution to privacy and security is *designing testable units* with specific features to ease testing and exposing internal information, for guaranteeing a given level of security and privacy. Ye et al. [101] propose a method for white-box testing of service compositions with minimal exposure of internal information about the participating services. They augment methods with event interfaces that expose encapsulated events and relaxed constraints, to check white box coverage, thus guaranteeing information hiding and privacy.

Zhu et al. [103] propose testing variants of existing services to enable third-party organizations to test the SUT while assuring non-disclosure of information, for instance, source code. The testing variants can be used in a collaborative setting in which test tasks are completed through the collaboration of various "test services," that are registered, discovered, and invoked at runtime using the STOWS ontology of software testing [104].

Bartolini et al. [8] propose testable versions of services to collect coverage reports, by means of services that do not disclose the internals of the SUT, while still providing coverage information.

Di Penta et al. [32] propose testable services to allow testers to send assertions checked by services. In this way, testers can obtain test results without directly accessing the monitored data.

Security is often addressed by creating *networks of trusted entities that communicate using secure channels*. Zhang [102] proposes an approach for dynamically testing web services for reliability before integrating a discovered service. The approach enables the node that hosts the web service to trust the testing mobile agent. Cooray et al. [22] rely on secure communication to assure the privacy of test execution logs and reports. Bertolino et al. [13] propose a method to test service compositions under the governance of a service federation. An online testing component triggers service testing requests that are indistinguishable from regular requests, thanks to an assertion signed by an identity provider, which grants a regular role to the test component. Tests are selected and executed proactively, so as to ensure the trustworthiness of the federation.

Finally, both Hummer et al. [48] and Murphy et al. [75] explicitly define privacy and security requirements but do not propose solutions to satisfy them.

8.4 RQ3: Findings

We conclude this section summarizing the key findings about monitoring, isolation, privacy, security.

- *Monitoring:*
  Monitoring is often overlooked: Many studies do not report details about monitoring, despite its importance: Thirty-one percent of the studies do not explicitly indicate what they monitor, and 34% do not report on *how* they monitor the SUT.
  Custom solutions for monitoring are prevalent: most monitoring solutions largely depend on the application context, testing objective and granularity.
  Heterogeneous monitoring is quite common: Many studies privilege events and states of the SUT over the environment. However, a significant number of studies monitor several information sources (9 of 53 studies that indicate *how* monitoring is done) and capture heterogeneous information (18 of 58 studies that specify *what* is monitored) to retrieve the data required for field testing.

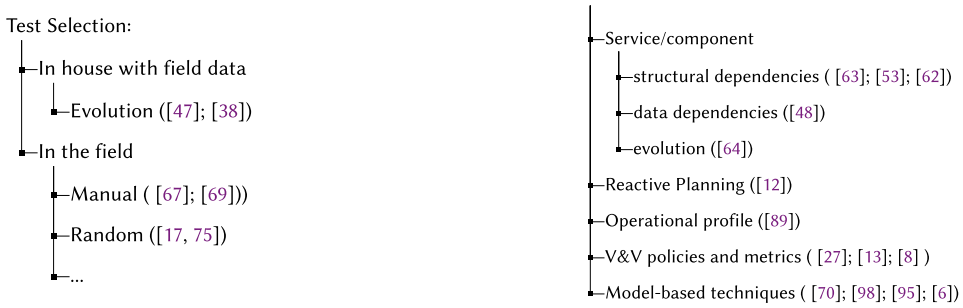


Fig. 10. Field testing approaches by test selection criteria.

- *Isolation:*
  The isolation problem is still largely open: Most approaches assume the availability of isolation mechanisms, leaving largely unexplored the many issues that derive from possible side effects on the state of the execution and on the environment, and from the interference with non functional properties, in particular performance.
  "Design for isolation" is often advocated: Many approaches assume the execution environment is aware of and supportive to field test execution, and define test cases that take advantage of the isolation primitives available in the execution environment, such as test execution mode and compensation mechanisms. This is frequent in approaches designed for the web service domain.
  Isolation policies largely ignore performance issues: Although some approaches proposes multiple alternative solutions for isolating field tests, there is no comparative evaluation of the performance footprint of the alternatives. As a consequence, the isolation policy is based on *a priori* assumptions on the effects of each choice, rather than on objective measures of their impact. Experiments that measure the performance overhead of the proposed isolation mechanisms are quite rare.
- *Privacy and Security:*
  Security and privacy are largely unaddressed: Very few studies address privacy and security issues in field testing, despite their importance, especially in some application domains, like web and service-based applications. Only one of the studies reported in this survey indicates security and privacy as a main focus [26].

9 RQ4: FIELD TEST SELECTION, PRIORITIZATION, AND GOVERNANCE

This section discusses test selection and prioritization (Section 9.1) and test governance (Section 9.2).

9.1 Field Tests Selection and Prioritization

Test selection is the activity of choosing a suitable subset of test cases to execute. Our investigation reveals a broad spectrum of techniques spanning from simple strategies like manual and randomized procedures, to sophisticated strategies like reactive planning and model based approaches. Figure 10 groups field testing approaches according to the proposed test selection strategies.

Few approaches select test cases in-house with data collected from the field. Frederiks et al. [38] and Hummer et al. [47] select ex-vivo test cases when observing changes of the system or its environment.

Lee et al. [67] and Loustarinen et al. [69] rely on *manual* test case selection based on domain knowledge, which may be accurate but slow and error-prone. Many approaches propose automatic

procedures. Bobba et al. [17] and Murphy et al. [75] rely on *random* selection, which is simple and fast, but gives no guarantees of accuracy and effectiveness of the selected test cases. Some approaches drive test selection using *information about the service or component* to be tested: King et al. [63] and Lahamani et al. [62] select test cases based on the structural dependencies to be tested, Hummer et al. according to data dependencies [48], and Lahami et al. according to information about the evolution of the unit under test [64].

Bertolino et al. investigate *reactive planning* solutions where the selection of test inputs is performed on-the-fly without requesting the generation of a test suite in advance [12]. Their auditing approach selects test cases at runtime guided by both the behavioral specification of the SUT (i.e., **Symbolic Transition Systems (STS)** [36]) and the output returned by the SUT at each interaction. Some approaches select test cases based on the *operational profile*. De Angelis et al. refer to modules that have been exercised less by users [89].

Other approaches select test cases according to policies and metrics relevant to the *V&V software process*. The works in References [13, 27] consider test selection as part of a test governance framework among a federation of services (see Section 9.2). A governance framework includes the validation of the conformance of each member to the specifications/behaviors prescribed in the federated context. Bartolini et al. [8] propose a framework that supports the anonymous collection of coverage information. The latter can be used either to support regression testing activities on the SUT or to reduce a test suite by selecting only those tests that actually contribute to the coverage improvement.

Some approaches drive test selection with *models* either inferred from observations or provided by testers: to capture the behavior of the SUT and select the test cases that are likely to reveal failures, Vain et al. rely on Markov models [95], Wang et al. on Petri Nets [98]. Bai et al. [6] and Ma et al. [70] use reinforcement learning and agent-based paradigms to reason about the behavior of the SUT, and select the test cases to be executed in reaction to changes in the operational conditions or in the software system.

Only few approaches address test prioritization, that is, a strategy for scheduling the order of execution of field test cases. Mei et al. [72] propose test prioritization without a selection strategy. They prioritize the execution of in-house tests based on changes that occur in the field to service compositions, assigning higher priority to the tests that are more likely to exercise the change. Vein et al. [95] use a probabilistic strategy. Few other approaches barely refer to some prioritization strategies without providing details [32, 73, 89].

9.2 Field Testing Governance

In general, governance is the act of administering, and relates to a set of policies, measures, practices and responsibilities to control and direct a complex system of relations and interactions. In the context of software development, governance refers to a framework that defines and coordinates the tasks, activities and roles of the software process. In the context of field testing, a governance framework provides a setting to execute and control testing activities, and establishes policies that guide the decision of when, how much, and how to test: *Test Governance* concerns the establishment and enforcement of policies, procedures, notations and tools that are required to enable test planning, execution and analysis of a given SUT [15].

We identify two dimensions that are relevant for field testing governance: Orchestration and User awareness. *Orchestration* concerns the strategy adopted or assumed to ensure that a proposed method or technology can be suitably embedded within the target application domain and successfully managed by all involved stakeholders. *User awareness* refers to the required or assumed degree of awareness of the end users of the SUT about the field testing activities: In some cases, the users might be informed and could be even asked to cooperate to the testing campaign, in

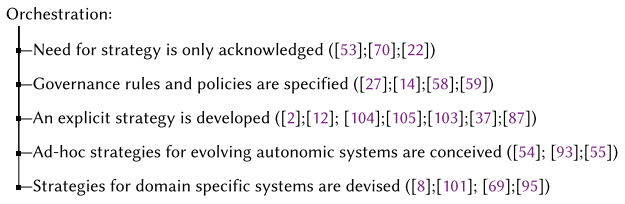


Fig. 11. Field testing approaches by orchestration strategy.

other cases the test could be conducted leaving the users blind about the fact that some executions are launched for testing purposes.

Figure 11 summarizes the orchestration strategies proposed for field testing. Only a small set of approaches explicitly deal with an orchestration strategy. Some approaches acknowledge the need to make assumptions behind the tested application, but do not propose an orchestration strategy. King et al. [53] mention that a *Test Manager* is in charge for test planning and management, and for evaluating test results "against the predefined test policies," which are available from a *knowledge repository*. Ma et al. [70] apply the *Belief-Desire-Intention* model for adaptive online performance testing, and assume a series of rules for deciding which services to test and how to allocate the testing tasks. In similar way, Cooray et al. [22] rely on the users of the testing system for supplying a test policy for each target service, whereby a test policy specifies the test configuration and schedule. However, not many details are given about such policies.

De Angelis et al. [27] and Bertolino et al. [14] propose different types of policies to support the orchestration strategy. They propose policies to decide when, how and what to test during field testing, without assuming a specific test framework. Skoll also allows the definition of strategies that control the testing process [87]. The TT4RT framework for runtime testing by Lahami et al. [58, 59] includes a description of policies for limiting side effects.

Several approaches propose an explicit orchestration strategy. Ali et al. [2] illustrate the strategy behind their proposed online testing framework for service choreographies. They describe both the involved stakeholders, including a choreography board, the testing engineers, the service providers and the choreography end users, and a schematic process for field testing. The PLASTIC framework [12] includes an online testing session for service admission, which requires an interaction protocol involving the requesting service, the registry, a Test driver, and a Proxy/Stub service factory. The framework proposed by Zhu and Zhang [104, 105] (originally outlined in a preliminary work [103]) is orchestrated around the provision of dedicated test services, both general-purpose and specific ones, and the STOWS ontology for web service testing that saves the information needed for the registration, discovery and invocation of such test services. Proteus [37] provides runtime testing for self-adaptive systems. The framework can adapt test suites and test cases so that both remain relevant despite changing operating conditions. The Proteus orchestration strategy is based on two basic rules: an adaptive test plan is provided at design time for each configuration and a testing cycle is executed at each new configuration.

King et al. [54, 93] and Stevens et al. [55] propose ad-hoc strategies for on-line self-testing of autonomic systems, for instance, at system evolution.

Few studies develop domain-specific strategies. In service-oriented architecture, the SOCT approach for *Service-oriented Coverage Testing* [8] is possible thanks to an orchestration strategy requiring that (i) the service provider releases an instrumented service, a.k.a *testable service*; (ii) a third-party service called TCOV provider collects coverage information, while (iii) a service consumer performs field testing of the service. Ye and Jacobson's approach [101] uses a similar orchestration strategy, assuming that instead of coverage information, the testable services espose

events that can be monitored through a dedicated interface by the third-party service. Luostarinen et al. [69] use field testing for remote usability testing, by requiring to natively integrate a dedicated API within the user interface. Vain et al. [95] propose testing in operation for mission-critical systems, with an orchestration strategy based on a model-based conformance testing approach.

Concerning user awareness, only few approaches explicitly address if and how the users are explicitly aware and involved into field testing. Niebuhr et al.'s approach [80] specifies the test cases executed at runtime by the Service Users. Luostarinen et al. [69] foresee that users actively participate to field testing by driving the requested usability tests. Skoll requires nodes to explicitly join the infrastructure to participate to the testing process [87].

In some cases even though the authors do not explicitly discuss user awareness, we can infer that users might indirectly become aware of the field testing activity, because during testing the system might be blocked or delayed. This may happen for the fault-injection technique by Alnawasreh et al. [3], or in the work by Lahami et al. [62], depending on which policy, among the four implemented ones, is selected to reduce the impact of field testing. In the work by Murphy et al. [76] the user would be warned in case the field test reveals unexpected behavior.

Some approaches explicitly make an effort to leave the user completely unaffected by execution of field tests using isolation solutions such as sand-boxing, as we discuss in Section 8.2.

9.3 RQ4: Findings

We conclude this section summarizing the key characteristics of field testing approaches with respect to test selection, test prioritization, and test governance.

- *Test selection*
  Test selection has been mostly investigated for in-vivo testing: The vast majority of approaches for selecting test cases focuses on in-vivo testing, where reducing the number of test cases to execute is extremely important, since the production environments typically offer limited resources for the execution of the test cases. Although less investigated, test selection techniques for ex-vivo testing can still be useful, when the ex-vivo test suites are particularly large.
- *Test case prioritization*
  Test case prioritization is poorly investigated in field testing: This is quite surprising, since running tests in the field can be both expensive and risky. Thus, optimizing test execution to anticipate the discovery of failures could be particularly relevant for large field test suites. However, most of the studies consider test suites of limited size for which prioritization is not likely to have a large impact. This might explain the outcome of our survey. We expect work on test prioritization to increase in the future.
- *Test governance*
  The importance of governance is undervalued: Field testing poses many challenges, and a proper governance framework becomes necessary for making field testing possible, specifically including a proper orchestration strategy and minimizing the impact on the end users of the production system. However, only 20 of the 80 studies discuss orchestration, and among those only 6 develop an explicit strategy. Only 6 approaches explicitly discuss users' involvement.
  Orchestration rules and policies are needed: In field testing, testers need to refer to appropriate rules and policies that establish when, how and by whom a selected set of tests can be executed. Some of the studies assume that such rules and policies exist, and the studies focus on the technical challenges. Only few studies propose some rules and policies,

even considering domain-specific contexts. However, most studies completely overlook the orchestration dimension.

Impact on users in production: The execution of field tests may directly or indirectly impact users' experience with the system under test. Only very few studies mention this issue, and take different research directions: either the users are made aware of field testing and is expected to actively participate, or an explicit effort is made not to affect users in any way.

10 DISCUSSION

Table 7 summarizes the main findings for each research question. RQ1 deals with the "how is software tested" dimension of field testing. Our survey shows that most approaches are based on *functional* testing, that is, test cases for field testing are derived from the functional requirements and in particular from formal or semi-formal specifications (e.g., finite state models). However, approaches for fully automated generation of field tests are still missing. Non functional aspects, such as quality of service attributes, have been investigated widely only within the service-oriented domain.

The main trigger for in-vivo testing is the in-field observation of a new or anomalous change in the execution environment or in the application under test itself (e.g., in case of a software update or re-configuration). Field test cases make use of data and computational resources available in the field, although such usage is not always analyzed in detail, despite its potentially negative impact on the end user experience. Since the in-vivo execution state is possibly unknown, developers of field test cases often rely on weak forms of oracles, such as metamorphic relations, that do not require a detailed analysis of all possible execution conditions and configurations.

RQ2 deals with the "what is tested" dimension of field testing. Field testing has been investigated at all granularity levels. There are examples of field testing approaches targeting individual units, such as functions or services, the integration of units, as well as the entire system. However, the types of systems being field tested are not evenly spread among all domains. Server applications that provide long running services to their users or to other applications have been extensively considered as case studies, although the scalability of field testing to larger federations of cooperating systems is still an unexplored research area. While combinatorial testing addresses the problem of the huge configuration space of software product lines, such testing approaches remain mostly confined to in-house testing and how to test those systems in the field is still a quite unexplored research area.

RQ3 deals with the "what is required" dimension of field testing. The most critical aspect of field testing is probably the creation of mechanisms to ensure isolation of field test executions. While some form of *a priori* test case design for in-vivo execution is unavoidable, there are major opportunities to develop a general purpose infrastructure that provides isolation services to in-vivo tests. The solutions available as research prototypes span from duplication to test mode execution, blocking and tagging, but no comprehensive and comparative assessment was carried out to establish their performance footprint, as well as their impact on privacy and security.

RQ4 deals with the "how is field testing managed" dimension. The main finding for this research question is that field testing policies are largely missing and under-studied. While proper governance of the field testing activities would be needed to ensure an even distribution of the testing load across application instances and to control that field testing is activated only when it provides a global added value with respect to the previously executed test cases, no such a comprehensive framework is available in the state of the art. Existing works focus only on some of the aspects of the field test management dimension, such as the selection of which test cases to execute or their prioritization.

Table 7. Summary of the Findings

RQ1: Approaches, Fault Types, Test Case Generation and Platforms	
Field testing mostly focuses on validating functional requirements, while non-functional aspects are under-investigated. The research on validating non-functional requirements in the field mostly focuses on QoS attributes. Specification-based test case generation is quite popular, but automatic synthesis of valuable test cases that can be safely executed in the field is still an open issue.	Section 5
RQ1: Source, Strategy, Triggers, Resources and Oracles	
While in-house and field test generation are widely studied, ex-vivo testing is clearly under-explored.	Section 6.1
Field testing is mostly exploited to anticipate failures and is commonly activated as a reaction to events from the SUT or on its environment.	Section 6.2
Data gathered from the production environment are the most relevant resource for in-vivo testing, however gathering such data requires additional engineering or infrastructures, not well addressed yet.	Section 6.3
Specification-based oracles are often exploited to reveal domain-dependent failures, but the oracle problem is sill largely overlooked. Suitable oracles are either not available or not usable.	Section 6.4
RQ2: Test Target, Granularity and Type of Tested Applications	
Field testing addresses a variety of target objectives: Overall it is an effective means to augment the validation activities that cannot be realistically completed in-house.	Section 7.1
Field testing applies to all levels from unit to system testing. However only few studies focus on scenarios foreseeing an opportunistic cooperation among complex systems. Research on field testing for Systems of Systems deserves more attention.	Section 7.2
Long-running server applications are extensively investigated: Some of the key challenges of in-vivo testing can be addressed by acting on additional dedicated resources. Despite the evolving configurations sensed by environment and the huge diversity of the devices are ideal scenarios advocating for in-vivo testing, mobile applications have not been frequently considered, probably due to the complexity of the mobile environment.	Section 7.3
RQ3: Monitoring, Isolation, Privacy and Security	
Monitoring is often overlooked: most studies do not discuss in detail which data are monitored and how, and rely on custom solutions tailored to the context. However, some studies investigate combined approaches that exploit several information sources.	Section 8.1
Isolating the SUT from the side effects due to field testing is still an open problem. The "Design for isolation" principle is often advocated, but isolation is usually not considered as part of the contributions. Automated isolation techniques mostly contribute to specific aspects. In general, performance studies estimating the overhead due to the adopted isolation mechanisms are rare.	Section 8.2
Security and privacy are largely unaddressed. Further investigation on approaches that specifically guarantee privacy and security in field testing is needed.	Section 8.3

(Continued)

Table 7. Continued

RQ4: Field Test Selection, Prioritization, and Governance	
Test selection and prioritization are mostly investigated for in-vivo testing. Although less investigated, test selection techniques for ex-vivo testing are still useful, when the size of ex-vivo test suites increases.	Section 9.1
The importance of a comprehensive governance framework is undervalued. Orchestration rules and policies are needed to establish when, how and by whom a selected set of tests can be launched. The explicit management of the impact on users in production has to be better considered and investigated.	Section 9.2

While we have designed our research questions to be as independent and "orthogonal" as possible, there are interactions among them. The absence of a well established framework for field testing governance affects the assessment of the isolation strategies. In fact, the performance degradation due to isolated in-vivo test execution depends on the overall governance of the field testing process, which eventually determines the frequency of field testing experienced by each running application instance. In turn, the effectiveness of test case generation, selection and prioritization depends on the effectiveness of the triggers that activate field testing. In fact, additional coverage can be achieved and additional faults can be exposed only if the right application state triggers the execution of the right test cases. Finally, the chosen oracle is a crosscutting factor that determines the effectiveness of all other in-field activities, since a weak oracle may not expose any fault despite the timely activation of the appropriate in-vivo tests.

10.1 Open Challenges for Researchers

Our survey identifies several open research challenges:

- **Generating and implementing field test cases:** Generating and implementing test cases designed for the field is still an open challenge. Field test cases shall adapt to the production environment, that is, they shall exercise the software system in the context of the production environment. Field test cases must offer a huge degree of openness and must deal with a high degree of uncertainty, since the field is not entirely known during development. Test cases with these characteristics have been mostly studied in the domain of service-based applications to test the interaction with dynamically discovered services. Consolidating the field testing practices to effectively address a wider range of situations is an important research direction. While existing approaches for test generation (especially specification-based ones) have been employed also for field testing, more advanced scenarios, such as the opportunistic generation of test cases in the field based on the characteristics of the underlying production environment, could also be conceived. These strategies are still underdeveloped and significant effort is still needed to move test case generation approaches from the development to the production environment.
- **Isolation Strategies:** Field test cases must be non-intrusive, that is, they should not interfere with the processes running in production and their data. There are many strategies to guarantee the isolation of the test cases, such as duplicating processes and components, enabling test modes, and selectively blocking executions. However, these strategies might be difficult and expensive to apply, depending on the domain and the test cases that must be executed. We need solutions that can be conveniently applied and adapted to specific

contexts, including approaches to design software ready to be field tested, and software components with built-in tests.

- **Oracle Definition:** Oracles for field testing need to adapt to the unknown execution conditions that can emerge in the field. Oracles checking abstract properties might miss relevant test failures, while oracles accurately checking the result produced by a field test might be extremely hard or even impossible to write. When specifications are available, they can be exploited to generate effective field oracles. However, defining oracles that can be effectively used in the field jointly with field test cases is largely an open research challenge.
- **Security and Privacy:** Executing test cases in the field challenges security and privacy. Indeed, the testing infrastructure can be potentially exploited to attack the software system, and the data mined from the field by field tests, for instance failure reports, may accidentally violate users' privacy. Security and privacy aspects have been under-investigated so far, and must be urgently addressed to move field testing to production.
- **Orchestrating and Governing Test Cases:** Field testing requires a disciplined approach, due to the potential impact on production: hence, testers need to refer to appropriate rules and policies that establish when, how, by whom, and in which order, a selected set of tests can be executed. Some of the studies just assume that such rules and policies are in place, thus bypassing the problem. The few studies that propose some rules and policies often consider domain-specific contexts. Research is needed to find appropriate governance strategies and establish the technical and organizational conditions under which such strategies can be actualized. However, the execution of field tests may directly or indirectly impact users' experience with the system in production, and it remains an open challenge how to mitigate or recover such impact after field test execution.
- **Challenging Domains:** Although field testing has been experimented in multiple domains, so far, field testing has been studied limitedly or not studied at all in other domains. In particular, the safety critical domain is extremely challenging for field testing, due to the consequences that an imperfectly isolated testing environment may have. Surprisingly, the mobile computing domain also received little attention, despite the huge variety of devices and environments mobile applications can interact with. This is likely due to the security constraints and limited resources present in mobile devices and their operating systems. Although challenging, these domains can greatly benefit from the field testing technology, and we expect more research in the future.

10.2 Guidelines for Practitioners

While answering the research questions along which we structured this survey, we made some observations that are of particular interest to practitioners in the industry.

- **Specifications:** Specifications are intensively used both for test generation as well as for identification of suitable oracles. However, it is also the case that specifications are not typically found in real systems, and when available are not specified formally, hence they are not suitable for automated processing. Practitioners in the industry, in particular when complex systems of systems are involved, could adopt development methodologies that make use of (formal) specifications, such as model driven development. This enables the effective application of automated in-vivo testing techniques and tools, in addition to addressing the general problem of test oracle definition.
- **Isolation:** One of the important findings of the survey is that isolation is critical for effective in-vivo testing. However, in many cases, achieving isolation during in-vivo test execution is far from trivial and remains still an open research problem. Practitioners could address it by

adopting design and development practices that are intrinsically compatible with isolation, making sure that side effects are kept at a minimum. When a system is planned to be tested in-vivo, developers should introduce isolation by design into the system.

- **Security and privacy:** Findings of the survey show that security and privacy concerns are mostly left unaddressed during in-vivo testing. While this could be partly attributed to research efforts trying to reduce the complexity of the problem by scoping out security/privacy concerns, it is also due to the fact that explicit policies outlining security and privacy related aspects of the systems under test are lacking. Practitioners adopting in-vivo testing should specify and document explicitly the security and privacy guidelines accompanying the system. This would support a compatibility check between the information access needed for in-vivo testing and the information restrictions enforced by such security and privacy guidelines.
- **Governance:** The survey findings show that the issue of comprehensive in-vivo testing governance is not addressed by the overwhelming majority of the works surveyed. While the research should do better to incorporate governance, this is also partly attributable to the lack of clearly defined governance frameworks from the systems under test. Practitioners should adopt a comprehensive governance framework that clearly defines the in-vivo process in the life-cycle of development and testing of the system. In this way, the in-vivo testing phase would play a specific role in the overall governance, which in turn determines the frequency of in-vivo test execution, its goals and the overall test data collection process. This is a core governance concern in highly distributed settings, with a multitude of diverse, geographically scattered users.

11 THREATS TO VALIDITY

The process of selecting and reviewing the articles is subject to the risk of bias. We hereafter report the potential validity threats and the actions we took to mitigate them.

Study identification/sampling: Selection of the primary studies can end up with anon-representative sample with respect to the investigated topic, for instance some relevant papers might have been included or excluded incorrectly. The first step of our search was by a keyword-based strategy on the *Sciverse Scopus DB*. Although it is a single source, *Scopus* is one of the largest general purpose **Databases** (DBs) for peer-reviewed literature and indexes journals/proceedings of the most common publishers including *Elsevier, Springer, Wiley, IEEE, ACM*. As general purpose DB, we preferred *Scopus* to *Google Scholar*, as the latter includes non-published literature (e.g., preprint), papers that are not scientific articles or not peer-reviewed (e.g., technical reports, theses and other grey literature). The search string was kept generic so as to cover as much relevant studies as possible; although this conservative approach has lead to a wide set, requiring an intensive manual filtering, it has mitigated the risk of missing relevant studies. Moreover, to complement the search, we ran a forward and backward snowballing step.

All the steps, from the initial filtering (from 1,238 to 434 studies) to the application of inclusion/exclusion criteria (from 434 to 48 studies) and to snowballing (from 48 to 80) were conducted, independently, by the four research units that the authors belong to: Each unit analysed a subset of the papers selected randomly from the whole set at each stage, discussing both within the unit and between the units with (plenary and one-to-one) online meetings, so as to agree on the papers to include/exclude and, at the same time, iteratively refine inclusion/exclusion criteria.

Another threat regards the **quality** of selected studies. To mitigate it, studies are searched among those indexed by Scopus, which considers only peer-reviewed studies (a well-established requirement for high quality publications), excludes grey literature, and filters out several low-quality conferences and journals. Inclusion/exclusion criteria are applied on each of the 434

studies to ensure to keep only studies pertinent to field testing. This indeed mitigates but does not eliminate the threat of low-quality studies.

Data extraction and classification, according to the defined dimensions, could also be biased by a subjective interpretation. To reduce such a risk, the extraction and classification were done according to a data collection form with 9 dimensions and 20 sub-dimensions defined to answer the four research questions, to record data and categorize the studies unambiguously. To validate the form, we used a *test-set* strategy [56, 84], in which subsets of 14 papers were assigned to each unit, with each paper reviewed by at least two units. The units classified the papers independently, and then discussed in plenary meetings so as to ensure that all the reviewers had the same understanding of the dimensions and of their alignment with the four research questions.

After the dimensions validation, the rest of the papers were assigned to the four units and classified independently. The results were discussed in several inter-units and in six plenary meetings. The process, involving all the authors in multiple iterations, also mitigates the interpretative validity threat, due to the researcher bias in interpreting the data, classifying the papers and map them to the final findings [84]. The experience and expertise of many of the authors in the field of software testing is an additional mitigation factor. Though, since this step involves human judgment, the threat cannot be eliminated.

In general, the best practices for literature reviews by Kitchenham et al. for studies selection and analysis have been followed as documented above [56], and we published the final categorization on the ACM Digital Library as supplemental online material of this manuscript, thus making our analysis easy to be replicated by other researchers.

The final findings derived from the collected evidences are with references to a wide variety of applications and domains. However, some findings could change if applied to applications/domains outside what observed. For instance, the evidence collected for test prioritization in field testing (Section 9.3) is mainly based on applications with small/medium test suites, hence our findings could change if larger test suite are considered.

12 CONCLUSIONS

Field testing techniques address the complexity, unpredictability, evolvability and size of modern software systems—challenges that in-house testing activities cannot manage satisfactorily due to the huge configuration space under which those systems can operate. This article surveyed the state of the art in field testing following four research questions that deal with the multiple dimensions of the field testing activities: (1) how field tests are generated, (2) what field tests are generated, (3) what is required to execute the field tests, and (4) how field testing is managed.

The area of field testing is a challenging one and the existing research has just scraped the surface. Among the directions for future research, the most promising ones include the automated synthesis of test cases with high added-value (e.g., coverage increase) associated with in-field execution; the creation of oracles that target those faults that escape in-house testing and are better exposed in the field; the execution of in-field test cases on end-user devices with limited computation, memory and energy resources, such as mobile phones; approaches to ensure privacy of the exchanged data and security of the application under test when in-field tests are executed; overall governance of the distributed execution of field tests across all available installations and users.

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