

Generating Accurate OpenAPI Descriptions from Java Source Code

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Abstract—Developers require accurate descriptions of Representational State Transfer (REST) Application Programming Interfaces (APIs) for a successful interaction between web services. The OpenAPI Specification (OAS) has become the de facto standard for documenting REST APIs. Manually creating an OpenAPI description is time-consuming and error-prone, and therefore several approaches were proposed to automatically generate them from bytecode or runtime information.

In this paper, we first study three state-of-the-art approaches, Respector, Prophet, and springdoc-openapi, and present and discuss their shortcomings. Next, we introduce AutoOAS, our approach addressing these shortcomings to generate accurate OpenAPI descriptions. It detects exposed REST endpoint paths, corresponding HTTP methods, HTTP response codes, and the data models of request parameters and responses directly from Java source code.

We evaluated AutoOAS on seven real-world Spring Boot projects and compared its performance with the three state-of-the-art approaches. Based on a manually created ground truth, AutoOAS achieved the highest precision and recall when identifying REST endpoint paths, HTTP methods, parameters, and responses. It outperformed the second-best approach, Respector, with a 39% higher precision and 35% higher recall when identifying parameters and a 29% higher precision and 11% higher recall when identifying responses. Furthermore, AutoOAS is the only approach that handles configuration profiles, and it provided the most accurate and detailed description of the data models that were used in the REST APIs.

Index Terms—OpenAPI Specification, Source Code Analysis, REST APIs

I. INTRODUCTION

Representational State Transfer (REST) [1] Application Programming Interfaces (APIs) are widely used for communication between web services. Due to the loose coupling, service developers require documentation of the REST APIs to correctly implement API calls to other services. The OpenAPI Specification (OAS) [2] serves as the de-facto standard for describing REST APIs, and the resulting OpenAPI descriptions are typically shared with other development teams [3].

The *OpenAPI description* represents a REST API in two sections. REST API endpoint paths and corresponding HTTP methods are located in the OAS section *#/paths*, and the data models received and returned by the REST API are contained

in the section *#/components/schemas*. The *#* represents the OpenAPI description's root. In the remainder of this paper, we use the term *method* when referring to the unique combination of endpoint path and HTTP method and the term *handler* when referring to the source code method handling the REST API call to clearly distinguish them.

Various tools [4] and research approaches [5]–[10] use OpenAPI descriptions, e.g., for visualization, testing, and test and client code generation, and rely on the description's accuracy. Manually creating OpenAPI descriptions is time-consuming and error-prone. Many automated approaches [11]–[14] require running the web service to generate the OpenAPI description. Hence, they require the domain knowledge to create a valid run configuration for the service and the infrastructure resources to run it.

Recently, two static analysis approaches emerged that generate REST API descriptions from Java source code and bytecode. Huang et al. [15] proposed Respector for generating OpenAPI descriptions from bytecode of web services created with Spring Boot [16] or Eclipse Jersey [17]. They compared Respector to AppMap [18], Swagger Core [12], SpringFox [19], and springdoc-openapi [11] and outperformed all four state-of-the-art tools for generating methods, parameters, and responses. Cerny et al. [20] proposed Prophet, an approach for statically analyzing REST APIs in Java Spring Boot projects. Prophet does not generate an OpenAPI description but creates a custom JSON output used as an intermediate format for visualizing microservice dependency graphs.

However, in an evaluation of the existing static analysis approaches, Respector and Prophet, we identified several limitations. First, they do not consider Spring profiles [21] and fail to correctly translate thrown exceptions to dedicated HTTP response status codes. Moreover, they do not accurately report the data models of a REST API, which is a requirement for the various tools building on an OpenAPI description.

In this paper, we aim to understand and address the shortcomings of existing approaches and present AutoOAS, our static analysis approach for generating more accurate and detailed OpenAPI descriptions. It detects exposed REST methods, parameters, responses, and data models directly from the Java source code. It considers Spring profiles and exception handling and accurately represents data models, including inheritance information. We implemented AutoOAS for the

Java framework Spring Boot. To the best of our knowledge, we are the first to present a static analysis approach for generating OpenAPI descriptions that considers Spring profiles and accurately describes the data models. In this paper, we address the following research questions (RQs):

- RQ1 What are the shortcomings of state-of-the-art approaches for generating OpenAPI descriptions?
- RQ2 How accurately does AutoOAS generate the OpenAPI description from Java Spring Boot source code compared to state-of-the-art approaches?
- RQ3 What is the runtime performance of AutoOAS compared to state-of-the-art approaches?

We compare AutoOAS to Respector [15], Prophet [20], and springdoc-openapi [11] which are the state-of-the-art approaches for extracting the OpenAPI description from bytecode, source code, and runtime reflection, respectively. For the evaluation, we used an existing dataset containing seven Java Spring Boot projects [15] and improved the ground truth of methods, parameters, and responses obtained from the source code. The results show that AutoOAS obtained the highest precision and recall for identifying methods, parameters, and responses, and was the only approach that correctly described data model inheritance hierarchies. In summary, this paper makes the following contributions:

- An improved dataset describing the REST APIs of seven Java Spring Boot projects.
- An analysis of the shortcomings of the state-of-the-art approaches for generating OpenAPI descriptions.
- Our approach AutoOAS addressing the shortcomings and thereby generating more accurate OpenAPI descriptions.

The remainder of this paper is structured as follows. Section II describes the dataset used for the evaluations and the improvements we performed. Section III discusses the shortcomings of existing approaches for generating OpenAPI descriptions. Our approach AutoOAS, which addresses the shortcomings, is presented in Section IV. In Section V, we evaluate the precision, recall, and data model representation quality of the OpenAPI descriptions generated by AutoOAS compared to existing approaches. In Section VI, we evaluate its runtime performance. Section VII discusses the implications and threats to validity, and Section VIII presents related work. Finally, Section IX concludes the paper.

II. EVALUATING AND IMPROVING THE GROUND TRUTH

For our evaluation of existing approaches, we used the dataset curated by Huang et al. [15] containing seven Java Spring Boot projects and a document reporting their ground truth (GT), i.e., the projects’ methods, parameters, and responses. Table I lists these projects and provides descriptive statistics.

During our evaluation of existing approaches, we found multiple errors in the GT by manually comparing the OpenAPI descriptions generated by existing approaches with the projects’ source code. All detected errors were discussed by at least two authors to avoid bias. In the following, we

TABLE I
DESCRIPTIVE STATISTICS OF THE SEVEN SPRING BOOT PROJECTS.

| Project | Java LoC | #methods | #parameters | #responses |
|-----------------|----------|----------|-------------|------------|
| CatWatch [22] | 6,454 | 14 | 36 | 19 |
| CWA [23] | 3,616 | 6 | 16 | 16 |
| OCVN [24] | 28,099 | 278 | 5,002 | 278 |
| Ohsome [25] | 10,597 | 159 | 1,937 | 159 |
| ProxyPrint [26] | 6,052 | 75 | 154 | 101 |
| Quartz [27] | 3,883 | 14 | 15 | 20 |
| Ur-Codebin [28] | 1,962 | 6 | 14 | 12 |

describe the errors and the improvements that we performed to create our improved GT+ dataset.

A. Profiles and Methods

Spring Boot allows developers to segregate parts of the web service and its REST API at runtime by using Spring Profiles [21]. In particular, it provides an `@Profile` class annotation assigning the corresponding class to one or multiple profiles. At runtime, it only instantiates the classes of active profiles based on the service configuration. For instance, the CWA project consists of two Spring profiles called *external* and *internal*. Both profiles contain the same method and due to Spring Boot’s constraint of unique methods, the two profiles cannot be simultaneously active at runtime. GT missed this constraint. We improved it by creating two separate service descriptions to consider this runtime behavior in our GT+. Moreover, GT contained incorrect paths for project Ur-Codebin. In particular, we found that `/api` prefixes were missing for all endpoint paths in the GT. We fixed the paths in GT+.

B. Parameters

We noticed that the GT does not contain parameter locations, e.g., path or query. Furthermore, it represents parameter objects as individual parameters based on the object’s fields. For instance, it represents a single parameter object with three fields as three individual parameters. As a single exception, the GT reports one object parameter in project CWA with the object’s variable name instead of its only field’s name. We renamed the parameter to its field name in the GT+ and adopted the flat representation of the GT. This enables us to evaluate the completeness of the object parameter fields generated by the approaches.

In project CatWatch, we discovered that the GT reported a parameter name as `sort_by` instead of `sortBy` and we updated our GT+ accordingly. Furthermore, one request body parameter for project CatWatch is missing in the GT. Similarly, project Quartz contains multiple request body parameters missed by the GT. After verifying their appearances in the source code, we added all of them to the GT+.

C. Responses

We performed multiple improvements on the responses for two reasons.

1) *Default response code*: The authors of the GT assumed that methods with the void return type and methods returning null translate to a *204 No Content* response code. However, Spring Boot returns *200 OK* by default and only returns *204* if the status code is explicitly set. We found and fixed this error in the projects OCVN, Ohsome, and ProxyPrint.

2) *Exception handling*: Spring Boot provides `@ExceptionHandler` annotations to translate uncaught Java exceptions in handlers to HTTP response codes, typically defined in a second annotation `@ResponseStatus`. However, the GT does not report many translated error response codes. For instance, in project CatWatch, four methods always throw an *UnsupportedOperationException*. The exception translates to the HTTP status code *403 Forbidden*, which we added to the GT+. We fixed such errors also in the projects ProxyPrint, Quartz, and Ur-Codebin.

III. SHORTCOMINGS OF EXISTING APPROACHES

In this section, we evaluate three state-of-the-art approaches for generating OpenAPI descriptions, namely Respector [15], Prophet [20], and springdoc-openapi [11], to answer RQ1.

A. Evaluation setup

We generated the OpenAPI descriptions for each project with each approach and compared them to GT+. Furthermore, we manually evaluated the data model representation quality based on the correct translation of Java types into OAS types and the correctness of the model schemas compared to the Java classes.

For Respector, we compiled the source code of each project to obtain the byte code necessary for its analysis. We used the compilation information contained in the GT dataset to ensure that we evaluated the same state as in the original evaluation of Respector. For springdoc-openapi, we took the OpenAPI descriptions that were generated by Huang et al. [15]. As in Huang et al., we could not find a valid run configuration for the three projects OCVN, ProxyPrint, and Quartz and, hence, could not generate the OpenAPI descriptions for them. Prophet generates custom JSON files as analysis output. It does not report the actual parameter and response schemas but only the string literals in the Java method signatures. A method description for project CatWatch is shown in Listing 1.

For our evaluation, we converted Prophet’s custom JSON files into OpenAPI descriptions containing the original endpoint paths (Line 4 in Listing 1), HTTP methods (Line 1), parameters (Line 2), and success responses (Line 3). Additionally, we analyzed each parameter to identify its Java annotations, type, and name. We analyzed the annotations to output request body parameters in the corresponding OpenAPI section. We output Prophet’s `returnType` property as the response schema for response code *200 OK*. We selected Spring Boot’s default response code because Prophet itself does not identify any response codes. Note, the enhanced output contains no schema information but only the class names extracted from Prophet’s string literals. In summary, we not only correctly converted the extracted information

```

1 { "httpMethod": "GET",
2   "arguments": "[@RequestBody(required=false)
   String scoringProject, @RequestHeader(value=
   =\"X-Organizations\", required=false)
   String organizations]",
3   "returnType": "java.lang.String",
4   "path": "/config/scoring.project",
5   [...] }

```

Listing 1. A snippet of Prophet’s output describing one method of CatWatch.

of Prophet but even enhanced its output by considering the `@RequestBody` annotation and setting the default response code for successful responses. We provide the conversion script for Prophet in our replication package [29].

In the following, we describe the common reasons for incorrect identifications of methods, parameters, and responses compared to the GT+ and incorrect data model representations compared to the source code.

B. Methods

Existing approaches did not always extract methods correctly because of the following four reasons.

1) *Spring profiles*: Project CWA uses Spring profiles to distinguish its runtime behavior (cf. Section II-A). The two profiles named *external* and *internal* each contain a handler exposing the same method but different parameters, response codes, and even a different response body.

Respector does not support Spring Boot profiles and only generated a single OAS description containing one of the two duplicate methods and all other methods of both profiles. Prophet correctly detected the duplicate method but reported all methods in the same file without information about their accessibility at runtime. Notably, the OAS prohibits duplicate methods for OpenAPI descriptions, and Prophet could only report both methods in the same file because of its custom output format.

springdoc-openapi did not report any methods or data models in the OpenAPI description of project CWA because we could not run the project with any profile. We argue that springdoc-openapi reports the correct subset of methods for the profile active at runtime because only these handlers are loaded at startup. However, therefore springdoc-openapi’s analysis requires re-starting the service for each profile.

2) *Constants in paths*: Prophet could not resolve constants in endpoint paths but instead reported the string literal as the path, e.g., `/api/ENDPOINT_NAME`. This especially affected the projects CWA and Quartz, which extensively use constants.

3) *Regular expression constraints*: Project OCVN uses regular expressions for several path parameters, encoded in the path string. Respector correctly generated the path but ignored the constraint in the parameter description. Similar to handling constants, Prophet wrongly retained the literal path string as the path.

4) *Request mapping annotations*: Prophet incorrectly identified the methods of handlers annotated with `@RequestMapping` in multiple projects. Sometimes, it identified only one method when the annotation defined multiple methods. It also misclassified some HTTP methods as

GET when the annotation defined another one. Furthermore, Prophet missed all `@RequestMapping` annotations which did not set any HTTP method, e.g., in project ProxyPrint. In this case, Spring Boot exposes the endpoint path with all HTTP methods, which was correctly reported by Respector.

C. Parameters

We identified the following three reasons for misidentifying parameters.

1) *Model attribute annotations:* Project OCVN extensively uses the `@ModelAttribute` annotation, which maps individual parameters to a single Java object. After inspecting Respector’s OpenAPI description, we discovered that it reported such parameters as a single request body object. However, Spring Boot does not bind the request body of the HTTP request to a model attribute object when receiving an API call [30]. Instead, it expects one path, query, or form parameter per object field, and builds the Java object correspondingly. Hence, API calls according to Respector’s OpenAPI description fail. We could not execute springdoc-openapi for project OCVN to evaluate its description of the `@ModelAttribute` annotation, and Prophet wrongly reported the model attribute parameter as a single parameter.

2) *Json property annotations:* Respector and Prophet both missed the `@JsonProperty` annotations in project Ur-Codebin, which translate Java class field names to data model field names. Only springdoc-openapi handled the annotation correctly and translated all parameter names.

3) *Request body annotations:* Respector missed one `@RequestBody` annotation in project CatWatch and four in project ProxyPrint. We could not explain why Respector missed these five instances because we could not observe any differences from other request body annotation occurrences. Prophet also missed the same annotation in project CatWatch, whereas it detected the four annotations in project ProxyPrint. Only springdoc-openapi correctly reported the parameter in project CatWatch, but it could not generate an OpenAPI description for project ProxyPrint.

D. Responses

We identified the following four reasons for misidentifying responses.

1) *Exception handler annotations:* All three approaches did not fully consider the `@ExceptionHandler` and `@ResponseStatus` annotations to translate exceptions to response codes (cf. Section II-C). For instance, the four methods in project CatWatch throwing the `UnsupportedOperationException` were incorrectly identified by all three approaches. While the exception translates to *403 Forbidden*, Respector reported it as *500 Internal Server Error*, and Prophet and springdoc-openapi reported *200 OK*.

2) *Propagated exceptions:* In the projects CatWatch and Quartz, several handlers propagate thrown runtime exceptions from their callees. Respector detected the exceptions but could not translate them to the correct response codes based on the `@ExceptionHandler` annotations. Prophet could not

identify the runtime exceptions because they are not part of the handler’s signature, and springdoc-openapi could not identify them from runtime reflection.

3) *Manual exception handling:* We discovered that project Ur-Codebin contains custom logic to translate thrown exceptions to response codes in the `@ExceptionHandler`-annotated methods. Respector reported *500 Internal Server Error* instead of the manually translated response codes. Prophet and springdoc-openapi did not detect any exceptions and consequently did not report any error response codes.

4) *Wrong success response codes:* Respector misidentified the success response codes of void handlers and handlers returning null as *204 No Content* (cf. Section II-C1). Prophet did not describe any response codes. We manually set the response codes for Prophet to *200 OK* in our conversion script. springdoc-openapi did not suffer from this shortcoming.

E. Data model representation

We reiterate that the GT+ represents all parameter object fields as individual parameters to evaluate the completeness of the objects generated by the approaches (cf. Section II-B). Furthermore, the GT+ only contains the response type, e.g., object, array, or primitive type, but not the schemas of response objects. Hence, as part of this evaluation, we explicitly assess the representation quality of data models in the generated OpenAPI descriptions. We define describing the data models in the `#/components/schemas` section and retaining their inheritance information as quality attributes. We did not consider Prophet for most of this comparison because it generates custom JSON structures instead of OpenAPI descriptions and does not analyze the schemas of data models.

1) *Objects and inheritance:* In addition to regular objects, the projects ProxyPrint and Quartz use derived objects, i.e., objects inheriting fields from a superclass, as request body parameters, and the projects CWA, ProxyPrint, and Quartz return derived objects as responses.

Respector generated anonymous schemas containing all object fields directly in the corresponding parameter or response section of the OpenAPI description. It did not generate any explicit schema information in the `#/components/schemas` section and thereby discarded the semantic information and relationships of the data models. Furthermore, it flattened all fields of derived objects used as parameters and thereby discarded the inheritance information. We also found that Respector did not consider the object hierarchy of responses at all. For instance, a method in project CWA returns a data model named `InternalTestResult` with multiple inherited fields. However, Respector only reported a single field, which is declared directly in the class, without considering the inherited fields.

springdoc-openapi placed data model objects in the `#/components/schemas` section of the OpenAPI description and referenced them in the corresponding parameter and response sections. However, we could not generate any OpenAPI descriptions containing derived objects from the dataset’s projects. To evaluate the representation quality of springdoc-openapi,

we created a minimal test project containing derived objects. We found that it flattened all inherited fields of the object into a single schema and, similar to Respector, discarded all inheritance information.

2) *Map data structure*: The projects CatWatch, OCVN, and ProxyPrint use the map data structure, also known as dictionary, in parameters and responses. The OAS describes maps as objects. It implicitly defines the map's key type as a string and provides the `additionalProperties` keyword for the map's value type [31]. We found that Respector did not describe the value type but only reported the data structure as a regular object without any other information. In contrast, `springdoc-openapi` correctly reported the type of the values with the `additionalProperties` keyword.

Answer RQ1: We identified several shortcomings with existing approaches that impact the quality of OpenAPI descriptions extracted from Spring Boot projects. They range from ignoring Spring profiles, over ignoring or incorrectly handling several Spring Boot annotations and exception handling, to incorrectly representing data schemas. This hampers the application of existing approaches to Spring Boot projects and motivates a new, improved approach that we introduce in the next section.

IV. AUTOOAS APPROACH

Based on the identified shortcomings, we propose our approach named AutoOAS for generating accurate OpenAPI descriptions from Java source code. AutoOAS uses Spoon [32] to parse and statically analyze the Java source code, its inheritance hierarchy, and annotations. It does not require byte code or a running, accessible service, which simplifies the OpenAPI generation process by omitting compilation, execution, and runtime dependency management. Currently, our approach is limited to Spring Boot projects. However, it can be extended to support other vendors and frameworks.

AutoOAS identifies all Java classes containing REST method definitions and groups them based on their assignment to Spring profiles. It generates one OpenAPI description for each profile. For this, it identifies the methods, parameters, and responses from the source code definitions and uses the information to generate the OAS `#/paths` section. Then, it detects the data models referenced as parameter and response objects and generates the corresponding schema information in the OAS `#/components/schemas` section. Notably, if a service configuration defines multiple active profiles at once, merging the individual OpenAPI descriptions is trivial because all methods must be unique at runtime, and data model classes must be unique at compile time. Therefore, OpenAPI descriptions are mergeable with set unions of their `#/paths` sections, which are disjoint, and `#/components/schemas/` sections, which are either disjoint or contain identical duplicates.

In the following, we present the three stages of AutoOAS in detail, maintaining the distinction between *method* and *handler* (cf. Section I).

A. Source code parsing

AutoOAS parses the project's source code with Spoon to identify all Java classes that contain method definitions. For this, AutoOAS detects annotations marking the parsed Java classes that expose methods as *controllers*, such as `@RestController`. It assigns each controller class to their assigned Spring profile set(s) or to all profiles, including the default profile, if they are not explicitly assigned to at least one. AutoOAS then generates one individual OpenAPI description for each profile as described in the following sections.

B. Generating OpenAPI methods, parameters, and responses

In this stage, AutoOAS generates the `#/paths` section of the OpenAPI description by analyzing all method definitions in the controller classes of a single Spring profile.

1) *Methods*: AutoOAS considers superclasses of controllers because they potentially contain additional configurations or methods. Starting from the controller classes, AutoOAS traverses each controller's inheritance hierarchy and identifies all Java methods, i.e., handlers, annotated with `@RequestMapping` or specialized HTTP method mapping annotations, e.g., `@GetMapping`, as method definitions. AutoOAS extracts the endpoint path and HTTP methods directly from the handler's mapping annotations.

2) *Parameters*: Next, AutoOAS analyzes the parameters. It identifies each parameter name and schema, i.e., Java type information, from the handler's signature. If a parameter annotation explicitly defines the parameter name, e.g., `@RequestParam("param_name")`, AutoOAS renames it accordingly. It also resolves the parameter location, i.e., path, query, or header, from the annotation. If a path parameter contains a regular expression (regex) constraint following the syntax `{parameter:regex}`, AutoOAS removes the regex from the path and adds it to the `pattern` constraint field of the parameter description.

AutoOAS converts parameter objects annotated with `@ModelAttribute` into individual query parameters based on the object fields. It also considers inherited fields by recursively iterating the object's inheritance hierarchy. The `@RequestBody` annotation marks a special parameter transferred in the HTTP request body, and AutoOAS uses the dedicated OAS keyword `requestBody` to describe it. Notably, AutoOAS does not describe object parameter schemas in-line but generates a reference to a named schema in the `#/components/schemas/` section of the OpenAPI description by using the `$ref` keyword. This enables the reusability of the service's data models.

3) *Responses*: AutoOAS analyzes each handler's body for `return` and `throws` statements to identify the responses. Handlers may return regular Java objects or `ResponseEntity<T>` objects, which wrap Java objects of type `T` and potentially set HTTP response codes. AutoOAS detects response codes returned by `ResponseEntity` objects from the source code. In case the handler has a void return type or no particular `ResponseEntity` or

explicit `@ResponseStatus` annotation could be identified, AutoOAS sets the response code to *200 OK*. AutoOAS extracts the data model schema of successful responses from the handler’s return type and references its named schema in the `#/components/schemas/` section.

Handlers may throw exceptions with the `throws` statement, resulting in HTTP client and server error codes. Spring Boot provides `@ExceptionHandler` and `@ResponseStatus` annotations to translate Java exceptions to HTTP response codes (cf. Section II-C). The Java method containing these annotations is either declared inside a controller to translate the exceptions of all handlers inside the same controller, i.e., local exception handling, or declared in a separate class annotated with `@ControllerAdvice` for translating the exceptions of any handler, i.e., global exception handling.

AutoOAS detects such exception-handling behavior. For this, it detects all classes annotated with `@ControllerAdvice` during the parsing stage described in Section IV-A to store the global exception handlers. When encountering a `throws` statement in a handler’s body, AutoOAS translates the thrown exception to a response code, with precedence on local exception handling. It first tries to identify a locally declared exception handler Java method for the thrown exception and resolves the corresponding response code. If it could not translate the exception, it searches the global exception handler Java methods for a matching exception to resolve the response code. Unresolved exceptions result in an *500 Internal Server Error* and are reported accordingly.

C. Generating OpenAPI data models

In this stage, AutoOAS generates the data models, i.e., the data objects transferred during API calls. We differentiate between two types of data models: simple types and named schemas. AutoOAS puts simple types directly into the corresponding parameter or response description and named schemas into the `#/components/schemas/` section of the OpenAPI description [33].

1) *Simple types*: AutoOAS supports Java’s built-in primitive and reference types, e.g., `int` or `String`. It maps primitive types and their wrapper objects to the basic types of the OAS [34], e.g., `int` to *integer*, `double` to *number*. It converts arrays and lists to the OAS *array* type, and explicitly lists Java enum constants in the OpenAPI description. It reports the map data structure, also known as the dictionary data structure, as an *object* and uses the `additionalProperties` keyword to describe the value type.

2) *Named schemas*: AutoOAS reports custom Java classes referenced in parameters and responses as named schemas in the OpenAPI description `#/components/schemas/` section. For this, AutoOAS records all Java classes referenced during the previous stage, which are the classes required to correctly interact with the described methods. AutoOAS generates the named schemas by describing the fields of each data model class. Additionally, it marks required fields of the schema with the OAS `required` keyword. AutoOAS considers fields

as required if they contain the `@NotNull` or `@NotEmpty` validation annotations or are primitive Java types which are not nullable, e.g., `int`.

If the data model class is a derived class, i.e., a class inheriting fields from a superclass, AutoOAS uses the `allOf` keyword [35] of the OAS to create a combined schema which contains the schema of the current class and a reference to its superclass. It then generates the named schema of the superclass and, if necessary, references its superclass again. Thereby, AutoOAS recursively scans the inheritance tree and retains the transitive inheritance information in the OpenAPI description instead of creating flat data model schemas, i.e., describing all fields in the same schema.

We argue that explicitly referenced and inheritance-aware schemas are necessary for correctly understanding and interacting with a service. First, referencing named schemas in parameters and responses helps developers understand the relationships between calls. For instance, two methods using the same schemas potentially belong to the same workflow or are potential API call chain candidates. Second, code generation tools require named schemas to correctly generate API consumers. For instance, they would generate multiple equivalent classes from duplicate anonymous schemas that are not compatible at runtime and, hence, not reusable in API call chains.

3) *Response wrappers*: Finally, AutoOAS automatically handles Spring’s `ResponseEntity<T>` and `DeferredResult<T>` response wrappers by extracting and reporting the type parameter `T`. If the type parameter is not specified, AutoOAS uses a special named schema called *UNSPECIFIED_TYPE*, and if it cannot infer the type, e.g., because the defining class is located in an inaccessible source package, AutoOAS creates a named schema from the class name and reports the package name in the OAS’s `externalDocs` field.

V. EVALUATION OF PRECISION, RECALL, AND DATA MODEL QUALITY

In this section, we answer RQ2 by evaluating AutoOAS on the GT+ described in Section II. We compare the precision and recall of AutoOAS, Respector, Prophet, and `springdoc-openapi` for identifying methods, parameters, and responses. Furthermore, we evaluate the data model representation quality, i.e., correctly referencing data models in the `#/components/schemas` section and retaining inheritance information. To generate the OpenAPI descriptions of Respector, Prophet, and `springdoc-openapi`, we reused the setup from Section III-A.

We created a script to automatically calculate precision and recall. First, for each approach, it transforms the generated OpenAPI descriptions into lists of methods, parameters, and responses per project. Next, it compares the list entries to the methods, parameters, and responses in the GT+. An identified method is a true positive (TP) if the endpoint path and HTTP method combination exists in the GT+, an identified parameter is a TP if the method and parameter name match with the GT+, and an identified response is a TP if the method and response

code match. The script also counts false positives (FP), i.e., identified methods, parameters, or responses not existing in the GT+, and false negatives (FN), i.e., not identified methods, parameters, or responses that do exist in the GT+. With these results, it calculates precision and recall as follows:

$$\text{Precision} = \frac{TP}{TP + FP}, \text{Recall} = \frac{TP}{TP + FN}.$$

We define the precision without any TP or FP findings as 0% to penalize approaches not reporting any methods, parameters, or responses. The results for each project for each approach are presented in Table II. In the following, we describe them in detail.

A. Methods

Only AutoOAS correctly identified all methods. It generated two OpenAPI descriptions with the correct subsets of methods for the two Spring profiles in project CWA. Furthermore, AutoOAS correctly captured the regular expression constraints of parameters defined in the paths of project OCVN and removed them from the path string.

AutoOAS and Respector both obtained an overall precision and recall of 100%. While Respector had a precision of 60% for both profiles in CWA, the project only contained three methods and, hence, did not have a noticeable impact on Respector’s overall precision. Prophet obtained 93% overall precision and 51% recall. Its results were only comparable to AutoOAS and Respector for two projects, Ur-Codebin and ProxyPrint. Moreover, Prophet did not detect any methods of the project CWA correctly because it could not resolve the constants in the endpoint paths. We observed the same shortcoming for Prophet in project Quartz.

springdoc-openapi achieved a low overall precision and recall (29% and 31%, respectively). This is because we could not find a valid run configuration for the three projects OCVN, ProxyPrint, Quartz, and no run configurations for the profiles *external* and *internal* of CWA. For the three projects, for which we could provide a run configuration, springdoc-openapi obtained comparable precision and recall values but still lower than the values of AutoOAS. We could not observe any noticeable differences between missed and identified methods of springdoc-openapi.

B. Parameters

We flattened the named schemas of AutoOAS, also considering the inheritance hierarchy, during the quantitative evaluation to compare them to the individual parameters of the GT+ (cf. Section II-B). Similarly, we flattened the objects of Respector and springdoc-openapi during the evaluation.

AutoOAS correctly identified and converted the `@ModelAttribute` annotations in project OCVN. Furthermore, it detected all parameters annotated with the `@RequestBody` annotation in the projects CatWatch and ProxyPrint. AutoOAS obtained an overall precision of 73% and recall of 69%, compared to Respector’s 34% for both, precision and recall. Prophet detected many parameters with

simple types but could not translate parameter names based on the parameter annotation, resulting in low precision and recall. Similarly, springdoc-openapi failed to correctly extract many parameters. AutoOAS missed several parameters in four projects due to the following reasons.

1) *No explicit parameter annotation*: Project OCVN contains many parameters that do not contain an explicit parameter annotation, e.g., for paging. AutoOAS did not detect such parameters.

2) *HTTP servlet objects*: Two projects use raw HTTP request and response objects encapsulating arbitrary parameters at runtime. Ohsome exclusively uses `HttpServletRequest`, and ProxyPrint uses `WebRequest`. AutoOAS could not detect the actual parameters encapsulated in such objects without fully analyzing the source code control and data flow. Similarly, springdoc-openapi ignored `HttpServletRequest` and `HttpServletResponse` objects per default [36]. Hence, AutoOAS and springdoc-openapi did not report any parameters in project Ohsome, resulting in 0% recall and precision. For project ProxyPrint, AutoOAS missed several parameters, and springdoc-openapi could not generate the OpenAPI description. Prophet naively reported all HTTP request and response objects as the parameters, resulting in 0% precision and recall for project Ohsome.

3) *Json property annotations*: AutoOAS incorrectly identified the eight `@JsonProperty`-annotated parameters in project Ur-Codebin, similar to Respector and Prophet. By ignoring the name translation, it created FP and FN findings. However, these instances are negligible, considering the total number of parameters for all projects. We leave the handling of this annotation to future work.

C. Responses

AutoOAS improved the detection of responses by correctly returning `200 OK` for void methods and methods returning null and considering exception handling annotations. It achieved an overall precision of 99% and recall of 97% for identifying responses, compared to Respector’s 70% precision and 86% recall and Prophet’s 89% precision and 46% recall. However, AutoOAS still missed responses in five projects.

1) *Propagated exceptions*: AutoOAS did not detect propagated exceptions from handler callees in the projects CatWatch and Quartz. The `throws` statements in callees are outside of the analysis scope of AutoOAS and therefore not considered. Respector’s symbolic execution identified many propagated exceptions but failed to translate them to the correct response codes.

2) *Propagated response codes*: Similar to propagated exceptions, AutoOAS did not detect `ResponseEntity` objects containing `201 Created` that are returned from handler callees in the two profiles of project CWA.

3) *Manual exception handling*: In project Ur-Codebin, AutoOAS and Respector reported `500 Internal Server Error` instead of the manually translated response codes, simultaneously resulting in FP and FN findings, and hence, low pre-

TABLE II

RESULTS OF THE FOUR APPROACHES WITH GT+. THE GT+ COLUMN CONTAINS THE NUMBER (#) OF METHODS, PARAMETERS, AND RESPONSES FOR EACH PROJECT. UNSUCCESSFUL ANALYSES ARE MARKED WITH AN "X". THE BEST RESULTS PER PROJECT ARE HIGHLIGHTED IN **BOLD**.

| Project | GT+ # | AutoOAS | | Respector | | Prophet | | springdoc-openapi | | |
|--------------|------------|-----------|-------------|-------------|-------------|-------------|-------------|-------------------|-------------|-------------|
| | | Precision | Recall | Precision | Recall | Precision | Recall | Precision | Recall | |
| CatWatch | methods | 14 | 1.00 | 1.00 | 1.00 | 1.00 | 0.60 | 0.21 | 1.00 | 0.57 |
| | parameters | 36 | 1.00 | 1.00 | 1.00 | 0.97 | 0.00 | 0.00 | 1.00 | 0.33 |
| | responses | 19 | 1.00 | 0.79 | 0.79 | 0.79 | 0.20 | 0.05 | 0.62 | 0.42 |
| CWA external | methods | 3 | 1.00 | 1.00 | 0.60 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | parameters | 10 | 1.00 | 1.00 | 0.69 | 0.90 | 0.00 | 0.00 | 0.00 | 0.00 |
| | responses | 8 | 0.86 | 0.75 | 0.22 | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 |
| CWA internal | methods | 3 | 1.00 | 1.00 | 0.60 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | parameters | 6 | 1.00 | 1.00 | 0.38 | 0.83 | 0.00 | 0.00 | 0.00 | 0.00 |
| | responses | 8 | 0.88 | 0.88 | 0.33 | 0.38 | 0.00 | 0.00 | 0.00 | 0.00 |
| OCVN | methods | 278 | 1.00 | 1.00 | 1.00 | 1.00 | 0.95 | 0.45 | x | x |
| | parameters | 5,002 | 1.00 | 0.95 | 0.06 | 0.06 | 0.06 | 0.00 | x | x |
| | responses | 278 | 1.00 | 1.00 | 0.81 | 0.89 | 0.95 | 0.45 | x | x |
| Ohsome | methods | 159 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 0.88 | 1.00 |
| | parameters | 1,937 | 0.00 | 0.00 | 1.00 | 0.99 | 0.00 | 0.00 | 0.00 | 0.00 |
| | responses | 159 | 1.00 | 1.00 | 0.35 | 0.85 | 1.00 | 0.50 | 0.88 | 1.00 |
| ProxyPrint | methods | 75 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.89 | x | x |
| | parameters | 154 | 1.00 | 0.80 | 1.00 | 0.95 | 0.31 | 0.22 | x | x |
| | responses | 101 | 1.00 | 1.00 | 0.97 | 0.97 | 0.99 | 0.66 | x | x |
| Quartz | methods | 14 | 1.00 | 1.00 | 1.00 | 1.00 | 0.07 | 0.07 | x | x |
| | parameters | 15 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | x | x |
| | responses | 20 | 1.00 | 0.75 | 1.00 | 0.80 | 0.07 | 0.05 | x | x |
| Ur-Codebin | methods | 6 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | parameters | 14 | 0.43 | 0.43 | 0.43 | 0.43 | 0.13 | 0.07 | 1.00 | 1.00 |
| | responses | 12 | 0.55 | 0.50 | 0.45 | 0.42 | 1.00 | 0.50 | 1.00 | 0.50 |
| Overall | methods | 552 | 1.00 | 1.00 | 1.00 | 1.00 | 0.93 | 0.51 | 0.29 | 0.31 |
| | parameters | 7,174 | 0.73 | 0.69 | 0.34 | 0.34 | 0.05 | 0.00 | 0.01 | 0.00 |
| | responses | 605 | 0.99 | 0.97 | 0.70 | 0.86 | 0.89 | 0.46 | 0.27 | 0.29 |

cision and recall. The exception handlers return the response codes *400 Bad Request*, *404 Not Found*, and *409 Conflict*. However, we argue that these misclassifications are negligible because other projects use the `@ResponseStatus` annotation. Prophet and springdoc-openapi did not detect any error response codes for this project, and hence, created FN but no FP findings. This resulted in a comparable recall but higher precision than AutoOAS and Respector.

D. Data model representation

Finally, we evaluate the quality of the extracted data models. AutoOAS described and referenced data model objects as named schemas in the `#/components/schemas` section. It used the `allOf` keyword to combine the schemas of derived objects and their superclasses while preserving the inheritance information. Listing 2 shows the schema for `InternalTestResult` of project CWA generated by AutoOAS. The response references the named schema with the `$ref` keyword in Line 6. This schema applies the `allOf` keyword in Line 10 and references its superclass in Line 11. In comparison, Respector identified only a single field and described the object as an anonymous schema, as shown in Listing 3. Prophet only reported the class name, and springdoc-openapi could not analyze the project.

We discovered that only AutoOAS reported required fields of named schemas, as seen in Listing 2 in Line 20 because the corresponding fields are primitive Java types `long` (Line 25) and `int` (Line 32). The other approaches missed these constraints in a total of 24 named schemas.

Answer RQ2: AutoOAS achieved the highest overall precision and recall when identifying methods, parameters, and responses. It outperformed the second-best approach, Respector, with an absolute 39% higher precision and 35% higher recall when identifying parameters and a 29% higher precision and 11% higher recall when identifying responses. Moreover, AutoOAS is the only approach retaining inheritance information of data models and the only static analysis approach considering inherited fields of responses.

VI. RUNTIME EVALUATION

In this section, we assess the runtime of AutoOAS and compare it to the other approaches to answer RQ3. We do not consider springdoc-openapi for this evaluation because it requires executing the service under analysis and exposes the OpenAPI description as an additional method. Hence, the runtime performance of springdoc-openapi mostly depends on the service’s runtime performance.

A. Evaluation setup

We executed all analyses on a virtual machine running Ubuntu 22.04 LTS, with four available cores of an AMD EPYC 7H12 CPU at 2.6 GHz and 16 GB of memory. For each approach, we analyzed each project five times and report the average runtime per project.

AutoOAS parses the Java source code with Spoon, which is configured to cache project class paths in temporary files. This speeds up repeated analyses of the same project. For this evaluation, we deleted all Spoon cache files before executing each analysis run, i.e., we measured the cold-start time of

```

1 "200" : {
2   "description" : "OK",
3   "content" : {
4     "application/json" : {
5       "schema" : {
6         "$ref" : "#/components/schemas/
          InternalTestResult"
7     } } } }
8
9 "InternalTestResult" : {
10  "allOf" : [ {
11    "$ref" : "#/components/schemas/TestResult"
12  }, {
13    "type" : "object",
14    "properties" : {
15      "testId" : {
16        "type" : "string"
17      } } } ] }
18
19 "TestResult" : {
20   "required" : [ "sc", "testResult" ],
21   "type" : "object",
22   "properties" : {
23     "sc" : {
24       "type" : "integer",
25       "format" : "int64"
26     },
27     "labId" : {
28       "type" : "string"
29     },
30     "testResult" : {
31       "type" : "integer",
32       "format" : "int32"
33     },
34     "responsePadding" : {
35       "type" : "string"
36   } } }

```

Listing 2. A generated response body for class *InternalTestResult* from AutoOAS representing the inheritance hierarchy with the `allOf` keyword in Line 10.

```

1 "200": {
2   "description": "OK",
3   "content": {
4     "application/json": {
5       "schema": {
6         "type": "object",
7         "title": "app.coronawarn.verification.model.
          InternalTestResult",
8         "properties": {
9           "testId": {
10            "type": "string"
11          } } } } } }

```

Listing 3. A generated response body for class *InternalTestResult* from Respector which contains one property, i.e., field.

AutoOAS. Respector is the only approach that requires bytecode for its static analysis. We compiled all projects before measuring Respector’s analysis runtime, i.e., we excluded this preprocessing step from the measurements.

Prophet is published as a Spring Boot web service. It receives the directory path(s) to one or multiple projects as an API call and returns the custom JSON format in the response. For this evaluation, we did not consider the one-time effort to start the Prophet web service and did not measure the conversion from the custom JSON format to the OpenAPI description. For each project, we measured the time taken to execute one `curl` command and to write the response body to

TABLE III
RUNTIME RESULTS OF THE APPROACHES IN SECONDS FOR EACH PROJECT.

| Project | Java LoC | AutoOAS | Respector | Prophet |
|------------|----------|---------|-----------|---------|
| CatWatch | 6,454 | 7.6 | 551.9 | 0.2 |
| CWA | 3,616 | 6.8 | 6.3 | 0.1 |
| OCVN | 28,099 | 31.4 | 11,577.5 | 1.1 |
| Ohsome | 10,597 | 9.8 | 9,499.3 | 0.7 |
| ProxyPrint | 6,052 | 8.8 | 447.6 | 0.3 |
| Quartz | 3,883 | 6.7 | 3.0 | 0.1 |
| Ur-Codebin | 1,962 | 5.8 | 2.7 | 0.1 |
| Average | 8,666.1 | 11.0 | 3,155.5 | 0.4 |
| Median | 6,052 | 7.6 | 447.6 | 0.2 |

the terminal output.

B. Runtime performance

We present the runtime results in Table III. Prophet analyzed the projects the fastest, with an average runtime of 0.4 seconds and a median of 0.2 seconds. However, Prophet only analyzed handlers and did not generate any data model schemas. AutoOAS obtained an average runtime of 11.0 seconds and a median of 7.6 seconds. It analyzed six projects in less than 10 seconds and one project, OCVN, in 31.4 seconds. We discovered that project OCVN is the only project with an invalid project configuration according to the IntelliJ Integrated Development Environment (IDE). Hence, we expect Spoon to take more time parsing the project correctly. For the other projects, we observed that the runtime of AutoOAS increases approximately linearly with the project size in terms of Java LoC. Notably, AutoOAS is the only approach without setup time. It is executable on the command line and only requires the Java source code as input. Respector was the slowest approach, with an average runtime of 3,155.5 seconds, i.e., 52.6 minutes, and a median runtime of 447.6 seconds, i.e., 7.5 minutes. We attribute the extensive runtime to the symbolic execution analysis, which identifies parameter constraints that are not part of the OAS.

Answer RQ3: AutoOAS was slower than Prophet but significantly faster than Respector, which generates parameter constraints not part of the OAS. We argue that the runtime performance of AutoOAS is reasonable, especially considering its higher precision, recall, and data model quality compared to Prophet and Respector.

VII. DISCUSSION

In this section, we discuss the implications and the internal and external threats to the validity of our evaluation.

A. Implications

AutoOAS offers higher applicability for practitioners than existing approaches for generating OpenAPI descriptions. This is because Prophet and `springdoc-openapi` require additional steps that complicate their usability. In particular, Prophet was published as a web service whose analysis is initiated via an API call, and `springdoc-openapi` requires running the service under analysis. Furthermore, Prophet outputs a custom format that cannot be directly used as an OpenAPI description. Respector simplified the generation of OpenAPI descriptions

by only requiring bytecode. However, it suffers from a long runtime due to its symbolic execution, limiting its applicability.

In contrast, AutoOAS is implemented as a command line tool that achieves adequate runtimes while providing high precision, recall, and data model representation quality. In this regard, it significantly outperforms existing approaches. Furthermore, AutoOAS can be directly integrated into the development process by running it anytime during the implementation phase without needing the bytecode or a valid run configuration. To initiate adoption by software developers, we also publish AutoOAS as GitHub action and GitLab template¹, enabling its use in continuous integration workflows.

B. Threats to validity

To mitigate threats to **internal validity**, we used an existing dataset with seven Spring Boot web services curated by Huang et al. [15] for evaluating the precision and recall of our generated OpenAPI descriptions. We discovered many mistakes in the dataset’s original ground truth, and the first and second authors inspected the source code of the corresponding projects to discuss and improve the ground truth. We publish our improved ground truth, the web service projects, the AutoOAS source code, and the reported detection precision and recall metrics as a replication package [29] for transparency.

To mitigate threats to **external validity**, we used seven Java Spring Boot projects that used multiple coding styles, third-party libraries, e.g., Project Lombok [37], and request handling paradigms, e.g., servlet objects and annotation-based programming. Additionally, the projects comprised various numbers of endpoint paths, HTTP methods, parameters, and responses to be detected. Accordingly, we demonstrated our approach’s applicability with the Spring Boot framework. Our approach can be extended to other Java frameworks by adopting the analyzed annotations. For instance, the Jersey framework uses the `@GET` annotation instead of Spring’s `@GetMapping` annotation [38]. We provide the source code of our approach to allow other researchers to do that.

VIII. RELATED WORK

In this section, we discuss related work on generating OpenAPI descriptions. According to Lercher et al. [3], OpenAPI is the de-facto standard in the industry to describe REST APIs. Many existing approaches require executing the service to generate its OpenAPI description and, hence, require domain knowledge to create a valid run configuration of the service and the infrastructure resources to run it.

Yandrapally et al. [13] proposed ApiCarv, a test suite generation approach that executes an existing UI test suite for a web service in the browser, infers additional UI tests, and generates the OpenAPI description for all identified calls. SwaggerHub Explore [39] and AppMap [18] are commercial products generating the OpenAPI description by recording REST API calls at runtime. Serbout et al. [14] proposed ExpressO, an approach to generate OpenAPI descriptions

for JavaScript’s Express.js framework. They intercepted the initialization stage of the service at startup and stored the initialized methods and their handler source code.

SpringFox [19] generated OpenAPI descriptions for projects developed with the Java Spring framework. However, the last contribution on GitHub was four years ago, and it was superseded by `springdoc-openapi` [11]. Both tools use Java reflection to analyze Spring annotations at the time of service startup. Both require adding the corresponding dependency to the project and expose the OpenAPI description as an additional service method. Swagger Core [12] generates OpenAPI descriptions for web services developed with the Java Jersey framework. Again, it uses runtime reflection and exposes an additional method for accessing the OpenAPI description.

Recently, Huang et al. [15] proposed Respector, the first approach to generate OpenAPI descriptions by statically analyzing Java bytecode. They compared Respector to AppMap, Swagger Core, SpringFox, and `springdoc-openapi` and outperformed all four tools for identifying methods, parameters, and responses. Additionally, they extracted parameter constraints by symbolically executing the bytecode. Furthermore, Cerny et al. [20] proposed Prophet to visualize microservice architectures reconstructed from the source code. They report the REST APIs of services in an intermediate format, subsequently used to map API calls to the corresponding service methods. For comparison reasons, we converted the intermediate format to OpenAPI descriptions.

To the best of our knowledge, no approach exists that can generate an OpenAPI description accurately representing Spring profile configurations, exception handling, and data models, i.e., object and inheritance information. Furthermore, many existing approaches require injection into the running service to generate the OpenAPI description, which complicates the automated analysis. AutoOAS addresses these shortcomings and, as a result, generates more accurate and detailed OpenAPI descriptions.

IX. CONCLUSION

In this paper, we proposed AutoOAS, our approach for automatically generating accurate OpenAPI descriptions for REST API web services from Java Spring Boot source code. AutoOAS addresses current shortcomings of the state-of-the-art approaches Respector, Prophet, and `springdoc-openapi`. It is the first approach that considers Spring’s profiles and exception handling by generating one OpenAPI description per profile configuration and translating potential exceptions in handlers, i.e., Java methods, into HTTP response codes. Moreover, AutoOAS is the first approach that accurately represents parameter and response objects, i.e., the data models of the REST API.

We evaluated AutoOAS on seven Java Spring Boot projects and compared the results to Respector, Prophet, and `springdoc-openapi`. The results show that AutoOAS outperforms the second-best approach, Respector, with a 39% higher precision and 35% higher recall when identifying parameters and a 29% higher precision and 11% higher recall when identifying

¹Removed for anonymity

responses. Furthermore, it is the only static analysis approach that considers the inherited fields for all data models. We observed that AutoOAS achieves these improvements at a median runtime of 7.6 seconds and maximum runtime of 31.4 seconds.

Future work concerns handling the missed annotations, e.g., `JsonProperty`, and detecting propagated response codes and exceptions to further improve the precision and recall of our approach. Furthermore, we plan to extend our approach to support other Java frameworks, such as Jersey [17] and Micronaut [40].

REFERENCES

- [1] R. T. Fielding, “Rest: architectural styles and the design of network-based software architectures,” *Doctoral dissertation, University of California*, 2000.
- [2] OpenAPI Initiative, “OpenAPI Specification v3.1.0.” <https://spec.openapis.org/oas/v3.1.0.html>. [Accessed 10-10-2024].
- [3] A. Lercher, J. Glock, C. Macho, and M. Pinzger, “Microservice api evolution in practice: A study on strategies and challenges,” *Journal of Systems and Software*, vol. 215, p. 112110, 2024.
- [4] APIs You Won’t Hate, “OpenAPI.Tools.” <https://openapi.tools>. [Accessed 10-10-2024].
- [5] I. Koren and R. Klamma, “The exploitation of openapi documentation for the generation of web frontends,” in *Companion Proceedings of the The Web Conference 2018, WWW ’18*, (Republic and Canton of Geneva, CHE), p. 781–787, International World Wide Web Conferences Steering Committee, 2018.
- [6] C. Peng, P. Goswami, and G. Bai, “Fuzzy matching of openapi described rest services,” *Procedia Computer Science*, vol. 126, pp. 1313–1322, 2018. Knowledge-Based and Intelligent Information & Engineering Systems: Proceedings of the 22nd International Conference, KES-2018, Belgrade, Serbia.
- [7] H. Ed-Douibi, G. Daniel, and J. Cabot, “Openapi bot: A chatbot to help you understand rest apis,” in *Web Engineering* (M. Bielikova, T. Mikkonen, and C. Pautasso, eds.), (Cham), pp. 538–542, Springer International Publishing, 2020.
- [8] S. Karlsson, A. Čaušević, and D. Sundmark, “Quickrest: Property-based test generation of openapi-described restful apis,” in *2020 IEEE 13th International Conference on Software Testing, Validation and Verification (ICST)*, pp. 131–141, 2020.
- [9] A. Arcuri, “Restful api automated test case generation with evomaster,” *ACM Trans. Softw. Eng. Methodol.*, vol. 28, Jan. 2019.
- [10] M. Kim, T. Stennett, D. Shah, S. Sinha, and A. Orso, “Leveraging large language models to improve rest api testing,” in *Proceedings of the 2024 ACM/IEEE 44th International Conference on Software Engineering: New Ideas and Emerging Results, ICSE-NIER’24*, (New York, NY, USA), p. 37–41, Association for Computing Machinery, 2024.
- [11] springdoc, “springdoc-openapi.” <https://github.com/springdoc/springdoc-openapi>. [Accessed 10-10-2024].
- [12] Swagger, “Swagger Core.” <https://github.com/swagger-api/swagger-core>. [Accessed 10-10-2024].
- [13] R. Yandrapally, S. Sinha, R. Tzoref-Brill, and A. Mesbah, “Carving ui tests to generate api tests and api specification,” in *Proceedings of the 45th International Conference on Software Engineering, ICSE ’23*, p. 1971–1982, IEEE Press, 2023.
- [14] S. Serbout, A. Romanelli, and C. Pautasso, “Expresso: From express.js implementation code to openapi interface descriptions,” in *Software Architecture. ECSA 2022 Tracks and Workshops* (T. Batista, T. Bureš, C. Raibulet, and H. Muccini, eds.), (Cham), pp. 29–44, Springer International Publishing, 2023.
- [15] R. Huang, M. Motwani, I. Martinez, and A. Orso, “Generating rest api specifications through static analysis,” in *Proceedings of the IEEE/ACM 46th International Conference on Software Engineering, ICSE ’24*, (New York, NY, USA), Association for Computing Machinery, 2024.
- [16] Spring, “Spring Boot.” <https://spring.io/projects/spring-boot>. [Accessed 10-10-2024].
- [17] Eclipse Foundation, “Eclipse Jersey.” <https://eclipse-ee4j.github.io/jersey/>. [Accessed 10-10-2024].
- [18] AppMap, “AppMap.” <https://appmap.io/>. [Accessed 10-10-2024].
- [19] springfox, “SpringFox.” <https://github.com/springfox/springfox>. [Accessed 10-10-2024].
- [20] T. Cerny, A. S. Abdelfattah, J. Yero, and D. Taibi, “From static code analysis to visual models of microservice architecture,” *Cluster Computing*, vol. 27, pp. 4145–4170, Jul 2024.
- [21] Spring, “Profiles.” <https://docs.spring.io/spring-boot/reference/features/profiles.html>. [Accessed 10-10-2024].
- [22] The Zalando Incubator, “CatWatch.” https://github.com/WebFuzzing/EMB/tree/master/jdk_8_maven/cs/rest/original/catwatch. [Accessed 10-10-2024].
- [23] Deutsche Telekom AG, “Corona-Warn-App Verification Server.” https://github.com/WebFuzzing/EMB/tree/master/jdk_11_maven/em/embedded/rest/cwa. [Accessed 10-10-2024].
- [24] Development Gateway, “Open Contracting Vietnam (OCVN).” https://github.com/WebFuzzing/EMB/tree/master/jdk_8_maven/cs/rest-gui/ocvn. [Accessed 10-10-2024].
- [25] GIScience Research Group and HeiGIT, “Ohsome API.” <https://github.com/GIScience/ohsome-api>. [Accessed 10-10-2024].
- [26] ProxyPrint, “proxyprint-kitchen.” https://github.com/WebFuzzing/EMB/tree/master/jdk_. [Accessed 10-10-2024].
- [27] Fabio Formosa, “Quartz Manager.” <https://github.com/fabioformosa/quartz-manager>. [Accessed 10-10-2024].
- [28] Mathew Estafanous, “Ur-Codebin.” <https://github.com/Mathew-Estafanous/Ur-Codebin->. [Accessed 10-10-2024].
- [29] Anonymous authors, “Generating Accurate OpenAPI Descriptions from Java Source Code - Replication Package,” Oct. 2024. <https://doi.org/10.5281/zenodo.13916835>.
- [30] Spring, “@ModelAttribute.” <https://docs.spring.io/spring-framework/reference/web/web/>. [Accessed 10-10-2024].
- [31] OpenAPI Initiative, “Model with Map/Dictionary Properties.” <https://spec.openapis.org/oas/v3.1.0.html#model-with-map-dictionary-properties>. [Accessed 10-10-2024].
- [32] R. Pawlak, M. Monperrus, N. Petitprez, C. Noguera, and L. Seinturier, “Spoon: A Library for Implementing Analyses and Transformations of Java Source Code,” *Software: Practice and Experience*, vol. 46, pp. 1155–1179, 2015.
- [33] OpenAPI Initiative, “Components Object.” <https://spec.openapis.org/oas/v3.1.0.html#components-object>. [Accessed 10-10-2024].
- [34] OpenAPI Initiative, “Data Types.” <https://spec.openapis.org/oas/v3.1.0.html#data-types>. [Accessed 10-10-2024].
- [35] OpenAPI Initiative, “Composition and Inheritance (Polymorphism).” <https://spec.openapis.org/oas/v3.1.0.html#composition-and-inheritance-polymorphism>. [Accessed 10-10-2024].
- [36] springdoc, “What are the ignored types in the documentation?.” <https://springdoc.org/#what-are-the-ignored-types-in-the-documentation>. [Accessed 10-10-2024].
- [37] The Project Lombok Authors, “Project Lombok.” <https://projectlombok.org/>. [Accessed 10-10-2024].
- [38] Oracle, “Developing RESTful Web Services with Jersey.” <https://docs.oracle.com/cd/E19776-01/820-4867/ggqmw/index.html>. [Accessed 10-10-2024].
- [39] Swagger, “SwaggerHub Explore.” <https://swagger.io/tools/swaggerhub-explore/>. [Accessed 10-10-2024].
- [40] Micronaut, “Micronaut.” <https://micronaut.io/>. [Accessed 10-10-2024].