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İÇİNDEKİLER

A CONTRACT-DRIVEN AUTOMATED UNIT TEST MAINTENANCE APPROACH WITH GENERATIVE ARTIFICIAL INTELLIGENCE FOR BACKEND SOFTWARE PROJECTS

Araştırma Makalesi

Sayfa: 74-97 / Yazarlar: Furkan Samet AKINCI, Tuğkan TUĞLULAR

REFLECTIONS OF VIRTUAL REALITY IN THE FIELD OF ARCHITECTURE: A CONTENT ANALYSIS OF MASTER'S AND DOCTORAL THESES IN TURKEY

Derleme Makale

Sayfa: 98-124 / Yazar: Minel KURTULUŞ



EDİTÖRDEN

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Bu sayıda yer alan ilk makalede Furkan Samet Akıncı ve Tuğkan Tuğlular tarafından kaleme alınan "A CONTRACT-DRIVEN AUTOMATED UNIT TEST MAINTENANCE APPROACH WITH GENERATIVE ARTIFICIAL INTELLIGENCE FOR BACKEND SOFTWARE PROJECTS" başlıklı araştırma makalesinde, üretken yapay zekâ destekli otomatik birim test bakım yaklaşımı önerilerek yazılım mühendisliği uygulamalarına katkı sunulmuştur.

İkinci çalışmada ise Minel Kurtuluş tarafından hazırlanan "REFLECTIONS OF VIRTUAL REALITY IN THE FIELD OF ARCHITECTURE: A CONTENT ANALYSIS OF MASTER'S AND DOCTORAL THESES IN TURKEY" başlıklı derleme çalışmasında, Türkiye'de mimarlık alanında sanal gerçeklik konulu lisansüstü tezler içerik analizi yöntemiyle incelenmiş ve alandaki akademik eğilimler ortaya konulmuştur.

Dergimize katkı sağlayan değerli yazarlarımıza ve makaleleri titizlikle değerlendiren hakemlerimize teşekkür ederiz. Akıllı Sistemler Dergisi'nin bilimsel üretime katkısını artırarak sürdüreceğine inanıyor, gelecek sayılarımızda da siz değerli araştırmacıların çalışmalarıyla desteklerinizi bekliyoruz.

Saygılarımızla,

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A CONTRACT-DRIVEN AUTOMATED UNIT TEST MAINTENANCE APPROACH WITH GENERATIVE ARTIFICIAL INTELLIGENCE FOR BACKEND SOFTWARE PROJECTS

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ABSTRACT

Modern backend systems frequently undergo changes in function contracts and API surfaces, which can quickly render unit tests outdated, brittle, or unusable. Most existing tools—whether based on classical test generation or large language models (LLMs)—focus on initial test creation, leaving the ongoing maintenance of existing test suites largely manual and error-prone. This paper presents a contract-driven, AI-assisted framework for unit test maintenance in TypeScript backend projects. The framework detects function-level contract changes and adapts related Jest tests through small, validated edits synthesized by an LLM, without creating new tests or performing broad refactorings. We evaluate the approach on 28 contract-change instances across four open-source projects. The results indicate that contract-driven, LLM-based test maintenance can act as a practical self-healing mechanism when contract changes are visible in the test surface, while its effectiveness remains strongly shaped by project architecture and test-suite design.

Keywords: Unit testing, test maintenance, artificial intelligence, contract changes, TypeScript, software evolution.

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ARKA UÇ YAZILIM PROJELERİ İÇİN ÜRETKEN YAPAY ZEKÂ TABANLI, SÖZLEŞME ODAKLI OTOMATİK BİRİM TESTİ BAKIM YAKLAŞIMI

ÖZET

Güncel arka uç sistemlerinde fonksiyon sözleşmeleri ve API yüzeyleri sık sık değişmekte, bu da birim testlerinin hızla geçerliliğini yitirmesine neden olmaktadır. Mevcut araçların büyük bölümü ilk test üretimine odaklanmakta, test bakımının önemli bir kısmı ise hâlâ manuel yürütülmektedir. Bu çalışma, sözleşme değişikliklerini kaynak düzeyinde algılayan ve ilişkili Jest testlerini büyük dil modelleri (LLM) ile yeniden üreten sözleşme odaklı bir bakım yaklaşımı sunmaktadır. Önerilen yöntem, TypeScript tabanlı dört açık kaynak arka uç projesinde toplam 28 sözleşme değişimi üzerinde değerlendirilmiştir. Deneyler, aracın başarısız koşulları otomatik olarak onarabilen, kısmi iyileştirmeler sağlayabilen ve mevcut test altyapısıyla bütünleşebilen pratik bir “self-healing” mekanizması sunduğunu göstermektedir. Bulgular, yöntemin başarısının proje mimarisi ve test suite kalitesiyle yakından ilişkili olduğunu da ortaya koymaktadır.

Anahtar Kelimeler: Birim testi, test bakımı, yapay zekâ, sözleşme değişimi, TypeScript, yazılım evrimi.

1. INTRODUCTION

Unit testing is a cornerstone of backend software quality, especially in systems where APIs and function contracts evolve continuously due to changing requirements, refactorings, and integration needs. Well-maintained unit test suites are essential for reliable continuous integration and continuous delivery (CI/CD) pipelines; they help detect regressions early and provide developers with fast feedback during evolution. In practice, however, keeping test suites aligned with an evolving codebase is costly and error-prone. Tests may silently become outdated, brittle, or unmaintained as interfaces and contracts drift over time [1].

Classical automated test generation techniques, including constraint-based and search-based approaches, have been proposed to mitigate the cost of writing tests from scratch. Constraint-based methods rely on symbolic execution to explore paths and generate inputs, while search-based and feedback-directed approaches such as EvoSuite and Randoop optimize entire test suites toward coverage criteria [2,3,5]. Although these techniques can achieve high coverage, several studies report that the generated tests often lack readability and meaningful assertions, which can make them difficult to maintain as systems evolve [4]. This challenge is particularly visible in backend services, where rapid changes in behavior, interfaces, and dependencies can expose weaknesses in automatically generated tests [1].

Recent advances in large language models (LLMs) have opened a new line of work on test generation and maintenance. Empirical studies show that LLM-based frameworks can produce human-readable tests with realistic assertions and can complement or outperform classical generation in certain settings [5–9]. Industrial deployments, such as Meta’s TestGen-LLM, demonstrate that LLM-based tools can be integrated into large-scale workflows and accepted by developers in practice [7]. Analysis indicates a number of key weaknesses. Firstly, results are largely dependent on the design of the target expression and the model used. Secondly, targeting coverage is still a challenge when it comes to achieving coverage.

Finally, most current systems are focused on generating tests from scratch rather than preserving existing target sets despite a contract change. [8–12].

In many backend projects, the primary source of test breakage is not the absence of tests, but the drift between function-level contracts (signatures, documentation, and shallow return shape) and the expectations encoded in the existing tests. If the name of the function changes, the parameters are altered in the function, or the documentation changes, multiple testing components need changes. For example, the calls, tests, and assertions need changes. Current best practices encompass manual implementations of the changes needed when the above modifications take place; in many ways, teams do not implement the changes fully, so tests may fail or be flaky.

This paper addresses this maintenance gap by proposing a contract-driven, AI-assisted approach to unit test maintenance. Instead of generating new tests from scratch, we detect function-contract changes at the source level and adapt existing Jest tests using small, validated edits synthesized by an LLM. The proposed framework:

- extracts and snapshots function contracts (signatures, normalized JSDoc, and shallow return-shape information) from TypeScript code,
- detects changes between baseline and current contracts,
- maps those changes to related source and test files,
- constructs guarded prompts for an LLM to propose minimal unified diffs or full-file rewrites, and
- applies these patches under strict Git-based validation and a bounded iterative repair loop.

We implement this workflow as the NPM package `@furkanakinci/contract-unit-test-maintainer` and evaluate it on four open-source TypeScript backend projects under 28 controlled contract-change instances. Our goal is not to maximize novelty at the algorithmic level, but to explore whether a relatively simple, contract-driven pipeline can provide a practical self-healing mechanism for existing unit tests in real backend projects.

The rest of the paper is organized as follows. Section 2 reviews related work on automated test generation, LLM-based testing, test repair, and contract-driven approaches. Section 3

details our methodology. Section 4 describes the experimental setup, including projects, change classes, and metrics. Section 5 presents the empirical results. Section 6 discusses implications and limitations. Section 7 concludes with a summary and directions for future work.

2. BACKGROUND & RELATED WORK

This section summarizes work related to automated unit test generation, LLM-based testing, test repair and maintenance, and contract/API-driven evolution. We focus on representative contributions and their limitations, emphasizing how they motivate a contract-driven, LLM-assisted maintenance approach.

2.1 Classical Automated Unit Test Generation

Search-based and feedback-directed test generation methods form long-standing baselines. EvoSuite optimizes test suite generation holistically. It optimizes the test suite for better coverage, size, and stabilization of oracles simultaneously. The experimental studies show performance improvements for the Java benchmark suite covering a wide set of applications [3]. Randoop introduced feedback-directed random testing, where candidate sequences are executed as they are built and only promising ones are extended, yielding practical bug-finding with modest setup cost [5]. For dynamically typed languages, Pynguin adapts these ideas to Python using reflection and evolutionary search to build runnable pytest suites and study flakiness and oracle brittleness [6].

These techniques primarily target initial generation. When system behavior or public contracts evolve, keeping assertions, fixtures, and helper code aligned with new expectations remains mainly a manual task. They are not inherently aware of contract drift, nor do they provide explicit mechanisms to adapt existing tests when function signatures or documentation change [4].

2.2 LLM-Based Test Generation and Early Maintenance

LLMs have recently been explored for generating and evolving unit tests. TESTPILOT evaluates LLM-generated JavaScript tests across many npm packages, reporting competitive statement and branch coverage and highlighting the importance of prompt composition and

error-driven retries [7]. Yang et al. systematically compare multiple LLMs against EvoSuite on Java projects, showing that performance depends strongly on the model and prompt configuration and arguing for controlled, reproducible evaluations [8]. Shang et al. evaluate 37 models across test generation, assertion generation, and test evolution, observing gains for larger and code-specialized models and for fine-tuning, while also warning about data leakage in benchmarks [9].

Several works aim to improve targeted coverage. HITS achieves better line and branch coverage by slicing complex focal methods and prompting per slice. This strategy performs better than basic prompting and even better than search-based baselines in complex methods [10]. TESTEVAL introduces a public benchmark with targeted coverage tasks, showing that fine-grained, path-level goals remain challenging for current models [11]. UTFix: It enhances automated testing by applying it to maintenance. It makes use of both static and dynamic slices and failure messages to guide the fix of existing tests. It has a very successful fix and re-coverage rate of changes, both synthetic and actual [12].

Despite this progress, most LLM-based approaches still focus on generating new tests or evolving them based on failures, without explicitly tying edits to a notion of contract change at the function level.

2.3 Test Repair and Maintenance Before LLMs

Before LLMs, several tools targeted automated test repair. ReAssert analyzes failing unit tests and proposes small program transformations (e.g., updating expected literals or changing assertion styles) that often match developer intent and reduce manual debugging effort [13]. For web UIs, capture–replay tests frequently break when the DOM changes; Imtiaz et al. model DOM differences and test scripts to repair breakages in locators, assertions, and added or removed elements, achieving high repair rates while preserving coverage and fault detection [14]. A systematic review by Imtiaz et al. catalogs prevention and repair strategies for test breakage, identifying which techniques have strong empirical backing and where industrial validation is still limited [15].

These works show that automated maintenance is feasible and valuable. However, they generally do not use explicit contract representations, nor do they exploit modern LLMs as a

flexible patch-synthesis engine.

2.4 Contract/API-Driven Testing and API Evolution

On the system side, OpenAPI/Swagger contracts support both automated testing and change analysis. RESTler uses contracts to generate stateful request sequences that respect data and resource dependencies, uncovering faults that simpler fuzzers miss [16]. EvoMaster consumes OpenAPI or Swagger schemas and can generate black-box or white-box system-level tests; white-box mode typically delivers higher coverage and fault detection [17]. Empirical studies on API evolution show that breaking changes are common and often insufficiently signaled; for example, many OpenAPI specifications introduce breaking changes without prior deprecation [18]. Usage-driven analyses recommend aligning evolution actions with common call patterns and highlight the need for better tooling and datasets [19,20].

These findings suggest that contracts are already effective drivers for system-level testing and evolution workflows. Our work brings similar contract-driven approach closer to the unit-test level, using function contracts as a structured signal for targeted maintenance.

2.5 Gap Analysis

Taken together, the literature indicates that:

- (i) classical generators are strong at creating tests but not inherently change-aware;
- (ii) LLM-based approaches can produce readable tests and support repairs but rarely focus on contract-driven maintenance;
- (iii) automated test repair is practical, but prior work seldom uses explicit contract representations; and
- (iv) contracts already underpin effective system-level testing and evolution analysis.

At present, a connection from function-level contract diffs to small, validated changes in existing unit tests is missing in contemporary research efforts. Also, this should be comprised of strong controls and be easily incorporable into daily programming routines. This gap motivates the methodology described in the next section.

3. METHODOLOGY

This section presents our contract-driven, minimally invasive pipeline for LLM-assisted unit test maintenance. The pipeline detects function-contract changes in a TypeScript backend, identifies related Jest tests, and uses an LLM to synthesize small, validated patches that realign tests with the updated contracts.

3.1 Objective and Scope

The objective is to track changes in function contracts and update existing Jest tests with the smallest possible edits so that they remain consistent with the evolved behavior. A function contract is defined as a tuple. This tuple contains the file path, the file name, and the raw TypeScript function signature. Moreover, it also contains the canonicalized “stableSignature,” the normalized JSDoc strings, and the return-object keys if it is statically analyzable. The framework does not generate new test files or perform broad refactorings; edits are restricted to aligning imports, call sites, fixtures, and shallow assertions with contract deltas.

3.2 Contract Extraction and Baseline

Contract extraction is implemented using ts-morph over the TypeScript abstract syntax tree (AST). For each exported function, we record:

- file path and function name,
- raw signature text,
- a stableSignature that normalizes fragile textual variation (e.g., spacing, parameter identifiers),
- normalized JSDoc with decorative characters and irregular whitespace removed, and
- a set of shallow returnObjectKeys when the return is a statically analyzable object literal.

The contracts are serialized to function-signatures.json. On first run, the snapshot is copied to function-signatures-base.json, which serves as the baseline. Baseline updates are explicit: only after a change is accepted do we refresh the reference snapshot. This separation between detection and acceptance prevents silent drift and makes contract changes auditable.

3.3 Contract Differencing and Change Set

To compute the change set, we normalize JSDoc strings, duplicate current and baseline snapshots into read-only “new” and “old” views, and match functions primarily by `stableSignature` (falling back to the raw signature otherwise). For each function, we compare:

- the `stableSignature` (or signature),
- normalized JSDoc, and
- JSON-encoded `returnObjectKeys`.

Any difference is treated as a contract change. We summarize return-shape differences as `retKeysDelta` to draw attention to additions, removals, or renames of shallow keys. The resulting `functionChanges` array is written to `change-combined-report.json`, and a dedicated process exit code indicates whether changes were detected, allowing CI to react.

3.4 Impacted Sources and Related Tests

The impacted source set is derived by deduplicating the file fields of `functionChanges`. A simple heuristic adds a sibling `*.service.ts` when a `*.controller.ts` file changes and both share the same stem, reflecting common layering conventions. Related Jest tests are discovered via `npx jest --listTests --json` and selecting tests whose filename stems match any impacted source stem. Optionally, an initial `jest --findRelatedTests` run provides a pretest signal: if all related tests pass, the maintenance step is skipped to avoid unnecessary LLM calls. If tests fail, we capture machine-readable JSON output including failure messages and stack traces.

3.5 Prompt Assembly and Size Control

We assemble an LLM prompt containing:

- a compact summary of the function contract changes affecting the target file,
- the content of the impacted source and related test files, and
- specific instructions to produce a minimal edit.

Prompt size is bounded by per-file and global character limits. Oversized files are truncated using a “head-tail truncation strategy” that preserves the beginning and end while marking the

elided middle with a sentinel comment. This keeps prompts within model limits while retaining the most informative regions. Each segment is labeled with its path, enabling file-specific instructions and validation.

We adopt description-dominant prompts: natural-language instructions carry the main task description, constraints, and success criteria, while short code-language cues (e.g., commented signatures) anchor concrete elements. This aligns with empirical findings that prompt style and coverage of relevant features significantly influence model performance [8].

3.6 Patch Synthesis, Validation, and Fallback

The primary path requests a unified diff for exactly one file, following the standard diff and patch format with `---` a/path, `+++` b/path, and `@@` hunk headers [22], [24]. The system role instructs the model to produce a minimal, correct patch in this format. The response is stripped of wrappers and validated structurally: it must reference the intended file and contain at least one syntactically correct hunk. We then run `git apply --check --index` as a dry run; only if this preflight passes do we apply the patch using a three-way merge (`git apply --index --3way`) [23]. Every accepted patch is archived for audit.

If no valid diff can be synthesized or applied, we fall back to a full-file rewrite path: the model is asked to return the complete revised file between explicit delimiters. We then overwrite the file and reconstruct a synthetic diff for traceability, again using standard diff conventions for logging and inspection [22], [24]. The fallback is restricted to a single file and is invoked only when the diff-first path fails.

3.7 Iterative Repair Loop and Safety Guards

When invoked in maintenance mode, the CLI enters a bounded iterative repair loop. Initially, patches are applied once to the related tests (or the subset that failed in pretest), and `jest --findRelatedTests` is run to obtain updated failures. If tests still fail and the configured iteration budget has not been exhausted, we issue a new LLM request per failing file, augmenting the prompt with the latest failure output. This process continues until all tests pass or the budget is consumed. All rounds log patches and test outcomes for later inspection.

The pipeline is subjected to certain safety invariants. Precisely, it forbids the generation of

new test code, prevents diffs involving multiple files, and denies improper patches. Additionally, changes to source code are conditioned by a specific configuration flag. Taken together, these requirements limit the LLM's override capability to localized patches that are auditable.

3.8 Implementation as NPM Package

We provide a reference implementation as the NPM package `@furkanakinci/contract-unit-test-maintainer` [29], written in Node.js/TypeScript. The tool integrates a variety of technologies. Specifically, it uses `ts-morph` for the extraction of contracts, `Jest` for the discovery and reporting of tests, the OpenAI Chat Completions API to make LLM calls, and `Git` for validation of patches. Furthermore, general utilities are used for the parsing and management of the CLI. [21,25–28]. All experiments in this paper use this package with configuration options matching the description above. The overall architecture and operation of the proposed pipeline are depicted in **Figure 1**.

4. EXPERIMENTAL SETUP

This section describes the research questions, subject projects, change classes, procedure, and metrics used in our evaluation.

4.1 Research Questions

We investigate the effectiveness and behavior of contract-driven, LLM-assisted maintenance under function-contract changes by addressing three research questions:

- **RQ1 – Success rate by change class and project.** For each change class and project, what proportion of runs ends with all related unit tests passing within the configured repair budget (considering only runs where pretest revealed failures)?
- **RQ2 – Repair effort and strategy.** In successful runs, how many repair rounds are required, what is the qualitative size of the accepted patches, and how often does the framework rely on full-file fallback instead of diff-first patching?
- **RQ3 – Overall effectiveness and failure modes.** Across all projects and change instances, what is the overall success rate, and how often do we observe partial

improvements, no-ops, or regressions in the test suite?

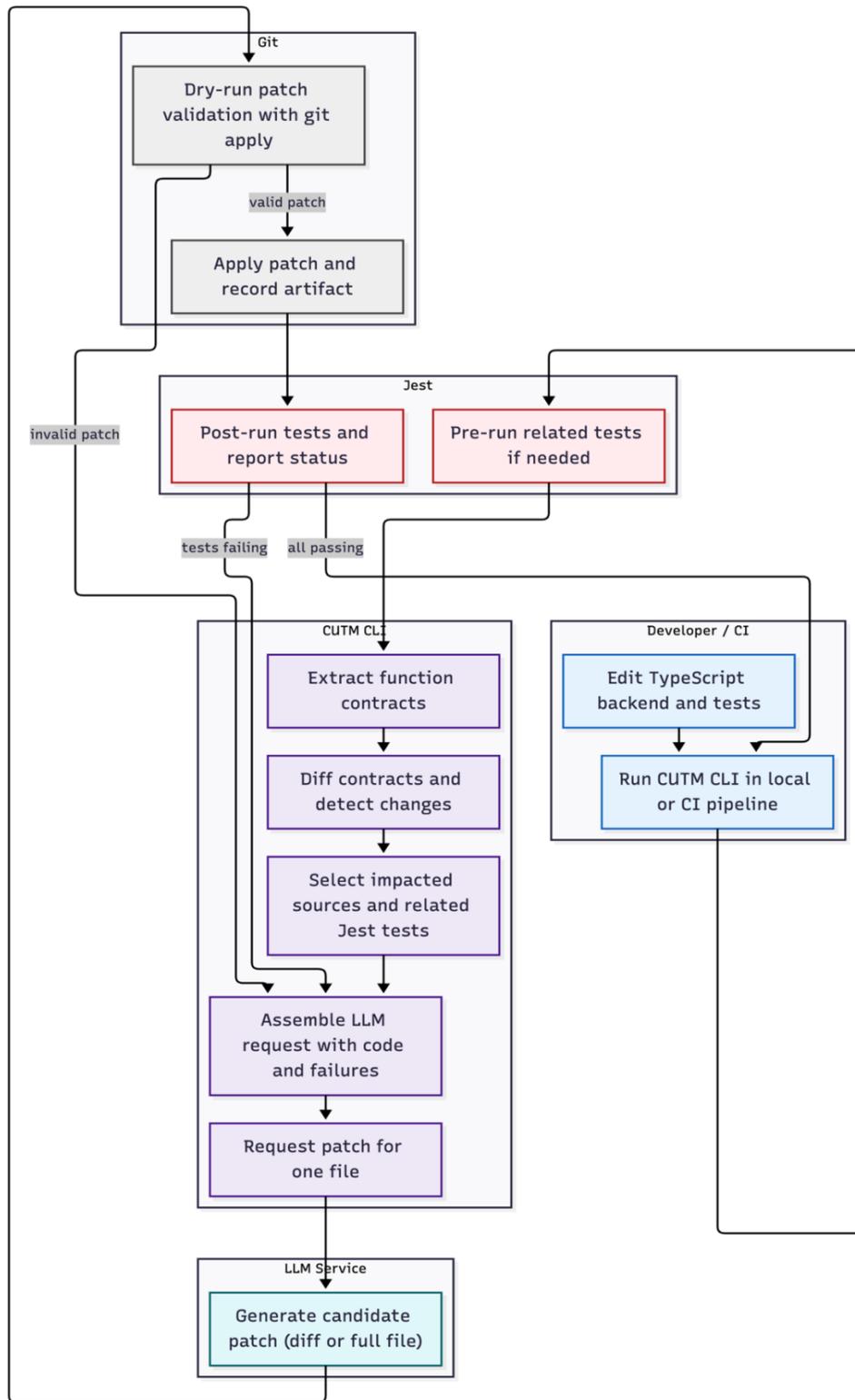


Figure 1. Pipeline of contract-unit-test-maintainer

4.2 Subject Projects

We evaluate the framework on four open-source TypeScript backend projects with existing Jest test suites:

- **P1: node-express-realworld-example-app (RealWorld)** – an Express-based implementation of the “RealWorld” reference backend.
- **P2: express-typescript-boilerplate (Express)** – a modular Express/TypeScript boilerplate with structured routing and configuration.
- **P3: nest-clean-architecture (Nest)** – a NestJS project following clean architecture patterns.
- **P4: screenpulse-backend-api (ScreenPulse)** – a backend API with layered modules and service abstractions.

The projects differ in architecture, complexity, and test design. P1 and P2 follow more traditional Express-style patterns with relatively dense unit tests, while P3 and P4 employ layered or modular architectures where some modules are lightly tested or have sparse assertions.

4.3 Change Classes

We apply seven change classes adapted from catalogs of interface and method changes [30-32], scoped to function-level contracts for unit tests:

1. **Function rename:** renaming a function (e.g., login → signIn), breaking imports and call sites.
2. **Parameter-list change:** adding or removing parameters, changing required/optional markers, or reordering arguments; these changes surface at call sites and fixtures.
3. **Parameter-type adjustment:** widening or narrowing parameter types at the signature surface, potentially misaligning mocks and type-based expectations.
4. **Return-shape change (shallow):** renaming, adding, or removing first-level keys in returned objects, breaking destructuring and shape-based assertions.

5. **Export-form change:** toggling between named and default exports, affecting import syntax.
6. **Lightweight module relocation:** moving a function to a new file while preserving its contract, causing stale import paths.
7. **Documentation-only change (control):** modifying or normalizing JSDoc without intended behavioral impact, serving as a non-breaking control.

Each change is introduced manually in a dedicated branch, affecting a single function contract at a time.

4.4 Procedure

For each project and change class, we follow a controlled workflow:

1. Start from a clean base commit with all tests passing.
2. Create a new branch and apply exactly one contract-level change from the list above.
3. Run the tool in check mode to detect contract changes and synthesize candidate patches without applying them.
4. Run the tool in apply mode to enter the iterative repair loop:
 - identify related tests,
 - optionally run pretests,
 - request patches from the LLM (gpt-5-mini),
 - validate and apply patches, and
 - re-run related tests until success or budget exhaustion.
5. Record artifacts: change reports, patch files, Git preflight output, and Jest JSON results.

After each experiment, we reset the repository to the base branch before applying the next change instance.

4.5 Metrics

Per change instance, we record:

- **Success (Tool Succ.):** whether all related tests pass within the configured repair budget.
- **Rounds-to-Green (RTG):** the number of repair iterations needed in successful runs.
- **Patch validity:** whether a syntactically valid unified diff was produced and accepted (vs. fallback).
- **Preflight result:** the outcome of git apply --check for diff-based patches.
- **Fallback usage:** whether the full-file rewrite path was invoked.
- **Test outcomes (pre/post):** number of failing test suites, failing tests, and passing tests before and after the tool's intervention.

These metrics allow us to answer RQ1–RQ3 while distinguishing partial improvements, regressions, and no-ops.

5. RESULTS

This section reports the outcomes of applying the framework to 28 contract-change instances across the four projects. For brevity, we refer to projects as P1–P4 and change classes as Ch.1–Ch.7.

Table 1 summarizes the per-project outcomes of our 28 change instances. For each project, we report the total number of applied contract changes, the number of fully successful repairs, and the resulting success rate. The last column (“Success ratio (successes/changes)”) captures how many of the seven changes for that project led to any positive effect on the test suite (e.g., fewer failing suites or more passing tests), even if the framework did not reach a fully green state.

5.1 Overall Outcomes and Metric Reliability

Across all 28 experiments, the tool reports success in 14 runs, yielding an overall success rate of 50%. In the remaining 14 runs, at least one test suite still fails after the repair budget is

exhausted.

A notable observation is the perfect alignment between the internal success metric (Tool Succ.) and the external ground truth (post-run Jest results):

- In all 14 cases where the tool reports success, all related tests pass at the end.
- In all 14 cases where the tool reports failure, related tests remain failing.

There are no false positives (claiming success with failing tests) and no false negatives (claiming failure with a green suite). This indicates that the internal success flag is a reliable proxy for externally observable correctness.

Table 1. Per-project repair success and improvement coverage across the four TypeScript backend projects.

PROJECT	# CHANGES	# SUCCESSFUL REPAIRS	SUCCESS RATE (%)	SUCCESS RATIO (SUCCESSSES/CHANGES)
P1	7	6	85.7	7/7
P2	7	3	42.9	5/7
P3	7	1	14.3	4/7
P4	7	4	57.1	4/7

5.2 RQ1 – Success Rate by Change Class and Project

RQ1 asks: For each change class, what percentage of runs ends with all related unit tests passing within the configured repair budget?

Success is not evenly distributed across change types or projects:

Change classes:

- Changes that manifest directly at imports and call sites—such as function renames and parameter-list changes—are often repaired successfully, especially in projects with explicit and focused tests.
- Export-form changes are also handled well when imports and usage patterns are straightforward.

- Return-shape changes and lightweight relocations are more sensitive to test design: they are easier to repair in suites with explicit destructuring and shape-based assertions, and harder when tests make only coarse-grained checks.

Projects:

- **P1** shows high compatibility, with successes in most change cases; this project combines a relatively rich test suite with straightforward architecture.
- **P2** and **P4** exhibit moderate compatibility, with a mix of successful repairs and failures.
- **P3** is the most challenging: the tool only succeeds in the documentation-only control case (Ch.7) and fails to reach full success for any active repair, reflecting the weaker and more fragmented test guidance in this project.

These observations form the basis of an important conclusion. Contracts and large language models work best when the test suite has visibility into the contracts and tests the primary call sites efficiently. On the other hand, success rates decrease if tests are sparse, poorly asserted, and skip the contracts.

5.3 RQ2 – Repair Effort and Role of the Fallback Mechanism

RQ2 asks: How many repair rounds and what kind of patches are typically required, and how often does the tool rely on fallback?

Across the 14 successful runs, the repair effort is low:

- Many successful repairs complete in a single iteration (RTG = 0), and no case requires more than a small number of rounds.
- Accepted patches are small and localized: edits usually touch a limited number of lines in one test file, or in a single test plus a closely related helper or import.

The fallback mechanism plays a central role:

- Among the 14 successes, 8 runs rely on the full-file fallback rather than diff-first patching.

- When we exclude the documentation-only control cases and focus on active repairs, 80% of successful repairs are achieved via fallback.
- Diff-based patches tend to work well when the structure of the test file is simple and easy to align, while fallback is more robust for complex or heavily refactored files.

This finding suggests that adaptive strategy switching is crucial. A purely diff-first approach would miss many successful repairs. At the same time, fallback remains constrained: it is applied to a single file and validated via Git and the test runner.

5.4 RQ3 – Overall Effectiveness, Partial Improvements, and Stability

RQ3 asks: What is the overall effectiveness of the approach, and what failure modes do we observe?

At the aggregate level, the framework reaches a fully green state in 50% of all runs. However, the binary success metric hides important structure:

Partial improvements:

Several runs labeled as failures show substantial progress. In P3 (Nest), multiple change instances start from a state where no tests can be executed successfully (all suites blocked by compile or configuration errors and zero passing tests). After the tool’s intervention, three out of four suites become executable, and many tests pass, even though one suite remains failing. Similar patterns appear in P1 and P2, where the number of failing suites is reduced but not fully eliminated. These cases demonstrate that the tool can “unlock” tests that previously did not run at all and move the system significantly closer to a healthy state.

No-ops:

In other failure cases, the test outcomes remain unchanged. Such cases occur mostly in P3. In the project, the complex layered architecture and insufficient test guidance hinder the LLM’s ability to infer the intended contract behavior.

Regressions:

In the dataset considered here, we do not observe regressions: none of the experiments end in a state worse than their pre-run condition in terms of failing suites and tests. This suggests

that the combination of Git-based validation, constrained patch scope, and explicit test reruns is effective in avoiding harmful changes.

Project-level performance reflects these modes: P1 benefits from dense, behaviorally rich tests and yields high repair rates; P3, with shallow and sometimes non-executable suites, poses a challenge and showcases the limits of contract-driven prompts alone.

5.5 Summary of Results

Across 28 contract-change instances in four TypeScript backend projects, the framework:

- achieves a 50% overall success rate in fully repairing failing test suites,
- relies heavily on its fallback mechanism, which enables 80% of successful active repairs, and
- exhibits no regressions, while still providing partial improvements in several runs labeled as failures.

These results show that contract-driven, LLM-based maintenance can serve as a practical self-healing mechanism for unit tests when contract changes are visible in the test surface. At the same time, its impact depends strongly on project architecture and test-suite structure, especially the extent to which tests encode and expose contract usage.

6. DISCUSSION

The experimental results highlight both the potential and the limits of contract-driven, AI-assisted unit test maintenance.

First, the alignment between the internal success metric and the ground truth indicates that our framework’s notions of “success” and “failure” are well calibrated. The tool never claims success when tests are still failing and does not miss any fully repaired case. This makes it suitable for integration into CI/CD pipelines: a “success” signal is trustworthy, and a “failure” signal reliably indicates that manual intervention is still required.

Second, the central role of the fallback mechanism shows that a single patching strategy is insufficient. In many real-world test files, especially those with historical edits or mixed

concerns, finding a minimal, structurally valid unified diff is hard for the model. Allowing a controlled full-file rewrite within strict validation boundaries compensates for this difficulty and is the main driver of successful repairs. At the same time, fallback is not a silver bullet: where tests are sparse or structurally misaligned with the underlying contracts, even full-file rewrites may not converge to a passing state.

Third, the notion of partial improvement complicates the interpretation of binary success rates. In several runs, especially in P3, the tool substantially improves the situation by turning previously non-executable test suites into suites with many passing tests, yet still leaves at least one suite failing. From a developer's perspective, these outcomes may still be valuable: the suite becomes inspectable, failure messages become more precise, and the remaining gap is smaller. Our current metrics treat such cases as pure failures; future evaluations could adopt graded metrics that explicitly account for partial recovery.

Fourth, the results underscore the dependence on test-suite quality and project structure. In P1, where tests are relatively dense and closely aligned with function contracts, success rates are high and repairs are often straightforward. In P3, many tests cannot run at all before repair due to configuration or contract mismatches, and assertions provide limited guidance. In this setting, contract-driven prompts alone are not enough to fully restore correctness. This suggests that our approach is best seen as a multiplier for existing, reasonably designed test suites rather than a replacement for sound test engineering practices.

Finally, from a methodological standpoint, the study exposes several design trade-offs:

- the balance between minimal diff-based edits and more invasive full-file rewrites;
- the granularity of contract features (e.g., shallow return keys vs. deeper behavioral models);
- and the choice of prompt style and repair budget for different projects and models.

These trade-offs will likely remain central in future work on LLM-assisted maintenance, especially as tools are deployed in more diverse codebases and organizational contexts.

7. CONCLUSION

This paper presented a contract-driven, AI-assisted framework for unit test maintenance in TypeScript backend projects. The approach detects function-level contract changes, identifies related Jest tests, and uses a large language model to synthesize small, validated patches that realign tests with the evolved contracts. The framework is implemented as an NPM package and was evaluated on 28 contract-change instances across four open-source projects.

The empirical results show that the framework can repair half of the failing scenarios, never introduces regressions in the examined dataset, and often yields partial improvements even when it does not fully succeed. Its strongest asset is the fallback mechanism, which enables most successful active repairs and acts as a robust complement to diff-first patching. At the same time, the success of the approach is not uniform: it depends heavily on project architecture and the quality and density of the existing test suite.

Overall, the findings support the view that contract-driven, LLM-based test maintenance is a practical self-healing mechanism when contract changes are exposed in the test surface and a reasonable test infrastructure is in place. For practitioners, the technique offers a way to reduce manual repair effort while preserving the structure and readability of existing tests. For researchers, the study suggests several directions: richer contract representations, more nuanced metrics for partial improvements, and broader evaluations across languages, frameworks, and model backends.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest regarding this study.

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REFLECTIONS OF VIRTUAL REALITY IN THE FIELD OF ARCHITECTURE: A CONTENT ANALYSIS OF MASTER'S AND DOCTORAL THESES IN TURKEY

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ABSTRACT

The transformative impact of digital technologies on the discipline of architecture is becoming increasingly evident. In this context, virtual reality (VR) technology contributes significantly to processes of interaction, representation, and presentation by offering a three-dimensional digital spatial experience. This study examines how VR technology has been addressed in the field of architecture in Turkey by analyzing a total of 36 master's and doctoral theses published between 1999 and 2024 in the Council of Higher Education (YÖK) National Thesis Center database (considering variables such as distribution by year, keywords, methodology, type of thesis, advisor title distribution, and university). The database search was conducted on June 2, 2025. The analyses reveal that the majority of the theses are practice-oriented master's research, whereas doctoral-level studies predominantly focus on theoretical frameworks and model development. Thematically, the theses concentrate on areas such as architectural education, spatial perception, visualization, urban design, cultural heritage, and construction safety. The most frequently employed approach is the mixed-methods design (qualitative + quantitative), highlighting the necessity of supporting the interactive nature of VR with multidimensional data. The study demonstrates that VR technology has the potential to enhance participatory design, creativity, and spatial awareness in both architectural education and practice.

Keywords: Virtual Reality, graduate theses, metaverse, digital technologies, architecture, virtual Reality

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SANAL GERÇEKLİĞİN MİMARLIK DİSİPLİNİNDEKİ YANSIMALARI: TÜRKİYE'DEKİ YÜKSEK LİSANS VE DOKTORA TEZLERİNİN İÇERİK ANALİZİ

ÖZET

Dijital teknolojilerin mimarlık disiplini üzerindeki dönüştürücü etkisi giderek belirginleşmektedir. Bu bağlamda, sanal gerçeklik (VR) teknolojisi, üç boyutlu dijital mekân deneyimi sunarak etkileşim, temsil ve sunum süreçlerine önemli katkılar sağlamaktadır. Bu çalışma, Türkiye'de mimarlık alanında VR teknolojisinin nasıl ele alındığını belirlemek amacıyla, YÖK Ulusal Tez Merkezi veri tabanında 1999–2024 yılları arasında yayımlanmış toplam 36 yüksek lisans ve doktora tezini (yıllara göre dağılım, anahtar kelimeleri, yöntemi, tez türü, danışman unvan dağılımı, üniversite vb.) incelemektedir. Tarama 02.06.2025 tarihinde yapılmıştır. Analizler sonucunda, tezlerin büyük çoğunluğunun uygulamaya yönelik yüksek lisans araştırmaları olduğu, doktora düzeyindeki çalışmaların ise kuramsal çerçeve ve model geliştirmeye odaklandığı görülmüştür. Tematik olarak tezler; mimarlık eğitimi, mekânsal algı, görselleştirme, kentsel tasarım, kültürel miras ve inşaat güvenliği başlıklarında yoğunlaşmaktadır. En sık tercih edilen yöntem karma yöntem (nitel + nicel) olup, bu durum VR'nin etkileşimsel doğasının çok boyutlu veriyle desteklenmesi gerekliliğini ortaya koymaktadır. Çalışma, VR teknolojisinin mimarlık eğitiminde ve pratiğinde katılımcı tasarımı, yaratıcılığı ve mekânsal farkındalığı artırma potansiyeline sahip olduğunu göstermektedir.

Anahtar kelimeler: Sanal gerçeklik, lisansüstü tezler, metaverse, dijital teknolojiler, mimarlık ve sanal gerçeklik

1. INTRODUCTION (GİRİŞ)

In recent years, the rapid advancement of digital technologies has brought about a profound transformation within the discipline of architecture, affecting a wide range of areas from design processes to presentation techniques, educational models, and user experience. At the core of this transformation lie virtual reality (VR) technologies, which, with their interactive and multisensory nature, enable users to have immersive experiences in three-dimensional digital environments that closely approximate reality, thereby demonstrating significant potential, particularly in design-oriented disciplines. Thanks to virtual environments that are constructed to resemble real spaces, the experience, testing, and presentation of architectural spaces have acquired a new dimension, positioning VR as a strategic tool for both pedagogical and professional applications.

Architectural education inherently encompasses skills such as materializing abstract concepts, experiencing spatial relationships, and critically evaluating design. Therefore, the opportunities

provided by virtual reality technologies have given rise to an important research domain in this field. Indeed, in Turkey, there has been a notable increase in academic interest in VR in recent years; it has been observed that, especially in the post-pandemic period, the acceleration of digitalization processes has led to a growing prevalence of these technologies in postgraduate theses.

In this context, identifying the reflections of VR technologies within the discipline of architecture, and evaluating in which thematic contexts, through which methodological approaches, and by whom these technologies have been studied, has become an important research need. To date, however, no comprehensive analysis has been conducted on postgraduate theses produced with the keyword “virtual reality” in Turkey, nor have the developmental trends in this area been systematically documented. This study aims to address this gap by examining a total of 36 master's and doctoral theses in the field of architecture, which are publicly accessible through the National Thesis Center of the Council of Higher Education (YÖK Thesis Center).

This analysis seeks to reveal the research themes, methodological tendencies, and institutional and academic advisor profiles associated with virtual reality within the discipline of architecture, while also providing a methodological and thematic framework for future research. In doing so, the study aims to contribute to a deeper understanding of how VR technologies are being integrated into architectural research and practice in Turkey.

2. LITERATURE REVIEW (LİTERATÜR TARAMASI)

Virtual reality (VR) technology has demonstrated remarkable development in recent years, particularly in the fields of architecture, education, and design. This technology is utilized across a wide range of application areas due to its significant effects on spatial perception, user experience, and the design process [1,2]. The use of VR in architectural education enhances students' spatial skills, increases their creative engagement, and facilitates the concretization of abstract concepts [3,4]. While virtual environments provide more interactive and immersive experiences compared to physical spaces, traditional environments stand out for their permanence and tangibility [5]. The integration of these two settings paves the way for holistic approaches in exhibition and cultural design. The presentation of historical buildings through VR not only raises awareness of heritage conservation but also improves the accessibility of cultural assets [6,7].

Wayfinding behaviors are another significant area influenced by VR technology. In complex facilities such as hospitals, the layout of floor plans directly affects users' wayfinding performance, while in virtual environments these behaviors can be analyzed more objectively

[8]. Additionally, transparent walls and distinct architectural elements play a crucial role in orientation and emergency scenarios [9]. In the context of urban design, VR encourages user participation in the design process, fostering more democratic and interactive practices [10,11]. However, technical challenges, hardware costs, and user habits remain significant barriers to the widespread adoption of this technology. Some studies emphasize that in order for VR to become an integral part of architectural practice, fundamental issues such as lack of knowledge must be addressed [12].

VR also plays an influential role in the construction sector and industrial transformation. Transformations in post-industrial areas based on principles of sustainability can be planned through VR scenarios to improve the quality of social life [13]. Innovative training applications developed with mobile VR and eye-tracking technologies further enhance occupational safety and user awareness [14]. Nevertheless, some researchers argue that VR can never fully replace real spaces and always remains a form of imitation [15]. However, many studies reveal that VR is a powerful tool that enhances user engagement and learning efficiency in both educational and professional contexts [16,17].

Overall, virtual reality technology, with its interactive, participatory, and creative experiences in diverse contexts, has become a key component of the digital transformation in architecture, education, and cultural domains. Although certain limitations persist, the literature indicates that VR is assuming an increasingly significant role in design and learning processes.

3. METHOD (YÖNTEM)

The primary aim of this study is to examine master's and doctoral theses focusing on virtual reality (VR) within the field of architecture in Turkey, from both thematic and methodological perspectives, in order to reveal the trends, diversity, and developmental dynamics of academic production in this area. In this regard, the study provides a multidimensional analysis of how VR technologies are addressed within the discipline of architecture, which topics are emphasized, which research methods are preferred, and within which institutional structures these studies are produced.

The scope of the study comprises a total of 36 postgraduate theses identified through a systematic search of the National Thesis Center database of the Council of Higher Education (YÖK Thesis Center) in Turkey. The search was conducted on June 2, 2025, using the keywords "sanal gerçeklik" (virtual reality) and "VR," and was filtered to the *title field* and limited to the field of architecture. The theses included in the analysis were systematically classified according to variables such as thesis year, thesis type (master's/doctoral), university, academic title of the advisor, research method used (qualitative, quantitative, mixed-method), keywords,

thematic focus, and main findings. Both descriptive statistical methods and content analysis were employed in the data analysis process. Quantitative findings include measurable data such as the distribution of theses by year, institutional concentration, advisor profiles, and methodological preferences. The qualitative analysis evaluates the thematic contexts in which VR is addressed in the theses, the approaches used, and the common themes identified in the results.

This methodological approach provides a comprehensive overview of the academic reflections of VR technologies within the discipline of architecture, making it possible to identify research trends, gaps, and future directions. Moreover, by offering a guiding framework for future postgraduate research, the study aims to serve as a reference for researchers in terms of both content and methodology.

4. ANALYSIS AND FINDINGS (ANALİZ VE BULGULAR)

Table 1. Thematic and Methodological Distribution of Postgraduate Theses on Virtual Reality in Architecture

Author/Year/Thesis Type	University/Title	Keywords	Method/Theme	Finding
Okuyucu, E./2024/MS.c	ITU/As soc. Prof. Dr.	x	Mixed/Quantitative – Qualitative – Healthcare Facilities and Virtual Reality	VR-based floor plan layouts provide objective insights into wayfinding behavior and spatial orientation in healthcare buildings.
Mercan, I./2024/MS.c	ITU/As soc. Prof. Dr.	x	Mixed/Quantitative – Qualitative – Urban Design and Virtual Reality	Virtual reality in urban design increases public participation and design awareness, but technical and cost constraints limit widespread adoption
Kılıç, Ş./2024/MS.c	Maltepe Uni./Asst. Prof.	Spatial perception, virtual reality experience, exhibition spaces, memory, perception	Mixed/Quantitative – Qualitative – Exhibition Spaces and Architecture	VR enhances spatial perception with immersive experiences, while physical spaces provide tangible and memorable encounters, highlighting the potential for integrated exhibition design.
Öztürk, S./2024/MS.c	Istanbul Aydın Uni./Asst. Prof. Dr.	Interior Architecture, Virtual Reality, VR, Design Studio, Interior Architecture Education	Quantitative – Interior Architecture and Virtual Reality	VR applications foster student engagement and creativity in interior architecture by supporting spatial awareness and conceptual clarity

Author/Year/Thesis Type	University/Title	Keywords	Method/Theme	Finding
Bektaş, O./2024/MS.c	Bursa Uludağ Uni./Prof. Dr.	Augmented Reality, Virtual Reality, Cultural Heritage	Quantitative – Cultural Heritage and Virtual Reality	Digital presentation of historical buildings via VR, multilingual support, and AI personalization increases cultural education and digital tourism potential.
Kurtuluş, M./2024/PhD	MSGSU/Prof. Dr.	Physical Environment Components, Virtual Learning Environment, Virtual Learning Space, VR Platform, Metaverse	Mixed/Quantitative – Qualitative – Virtual Learning Environment and Virtual Reality	VR-based educational environments demonstrate that physical environmental factors affect user experience, informing the design of virtual learning spaces.
Yasak, U./2024/MS.c	Yıldız Teknik Uni./Asoc. Prof. Dr.	Wayfinding, emergency evacuation, visibility, virtual reality, architectural design	Mixed/Quantitative – Qualitative – Emergency Scenarios and Virtual Reality	Transparent walls and architectural elements in VR settings improve wayfinding performance and evacuation behavior.
Kömürcü, T./2024/MS.c	Dumlupınar Uni/Prof. Dr.	Interior Architecture Education, Material, Space Design, Spatial Perception, Virtual Reality	Mixed/Quantitative – Qualitative – Interior Architecture and Virtual Reality	VR in interior architecture education strengthens spatial perception, offering a more effective and practical learning process than conventional methods.
Atahan, D./2024/MS.c	Balıkesir Uni./Asoc. Prof. Dr.	Virtual Reality (VR), Augmented Reality (AR), construction sector, technological innovations, digital transformation, data analysis, smart construction, technological integration	Qualitative – Construction Sector and Virtual Reality	VR, AR, and MR technologies enhance project management, visualization, and sustainability in construction, contributing to digital transformation
Coşer, H./2024/MS.c	ITU/Prof. Dr.	Virtual Reality in Urban Design, Urban Space Simulation, User Experience in Virtual Space, Neuro-Architecture	Mixed/Quantitative – Qualitative – Urban Space and Virtual Reality	VR supports safer and more participatory urban space design by improving user perception and interaction.
Taştan, H./2023/PhD	Yıldız Teknik Uni./Asoc. Prof. Dr.	Immersive Virtual Reality, architectural education, spatial skills, building components, cognitive load,	Mixed/Quantitative – Qualitative – Architectural Education and Virtual Reality	VR-based teaching models enhance spatial skills, cognitive load management, and learning performance in architecture education.
Usta, B./2023/MS.c	Yıldız Teknik Uni./Asoc. Prof. Dr.	Virtual reality, architectural representation, design	Qualitative – Architectural	High sense of presence in VR strengthens information transfer and user collaboration in the architectural design process.

Author/Year/Thesis Type	University/Title	Keywords	Method/Theme	Finding
	soc. Prof. Dr.	process, presence, performativity	Design and Virtual Reality	
Doma, O./2023/PHD	ITU/Prof. Dr.	x	Mixed/Quantitative-Qualitative – Virtual Education and Virtual Reality	VR supports creative design exploration during conceptual stages, becoming an effective design tool for practice and education.
Taşdelen, M./2023/MS.c	ITU/Asoc. Prof. Dr.	x	Mixed/Quantitative-Qualitative – Game-Space and Virtual Reality	Individuals with design education exhibit higher spatial performance in VR environments, validating its role in architectural training.
Kabır, M./2023/MS.c	ITU/Asst. Prof.	x	Mixed/Quantitative-Qualitative – Biophilia and Virtual Reality	VR-assisted design scenarios for post-industrial sites support sustainable and biophilic transformations, improving local quality of life.
Karadallı, Ş./2022/MS.c	DEU/Prof. Dr.	Conservation of Historical Environment, Virtual Reality, Presentation, İzmir Kemeraltı Bazaar and Inns Region	Mixed/Quantitative-Qualitative – Historical Environment Conservation and Virtual Reality	VR enhances accessibility and awareness in historical heritage conservation by digitally presenting historical sites.
Şarkışla, M./2022/MS.c	Erciyes Uni./Asst. Prof. Dr.	Architectural Representation, Representation Techniques, Spatial Perception, Raumplan, Free Plan, Müller House, Farnsworth House	Mixed/Quantitative-Qualitative – Spatial Perception and Virtual Reality	VR outperforms 2D techniques in complex architectural spaces by improving spatial perception in multisensory contexts.
Kılıç, E./2021/MS.c	ITU/Prof. Dr.	x	Mixed/Quantitative-Qualitative – E-Commerce and Virtual Reality	VR-based e-commerce applications strengthen user experience and loyalty by enhancing product perception.
Şahin, A./2021/PhD	Karatay Uni./Asst. Prof. Dr.	Basic design, design education, perception, spatial perception, virtual reality, learning to learn, guided exploration, learning styles	Mixed/Quantitative-Qualitative – Virtual Education and Virtual Reality	VR enriches basic design education by boosting spatial awareness, creativity, and learner engagement.

Author/Year/Thesis Type	University/Title	Keywords	Method/Theme	Finding
Özdoğan, M./2021/MS.c	Konya Teknik Uni./Prof. Dr.	Architectural Education, Virtual Reality, Virtual Environment, Building Knowledge, Generation Z	Mixed/Quantitative-Qualitative – Virtual Education and Virtual Reality	VR systems improve Generation Z students' understanding of structural courses by strengthening spatial cognition.
Özgün, S./2021/MS.c	Gazi Uni./Asoc. Prof. Dr.	Space Production, Cyber Space, Visual Culture, Spatial Interface, Virtual Reality	Quantitative – Space and Virtual Reality	Cyber-space formed by architecture, art, and technology merges physical and virtual realms into multilayered and dynamic spatial experiences.
Turhan, Ü./2020/MS.c	ITU/Asoc. Prof. Dr.	x	Mixed/Quantitative-Qualitative – Games and Virtual Reality	VR technologies foster realistic spatial perception, memory retention, and design skills in children's play and learning processes.
Sevim, H./2019/PhD	Konya Teknik Uni./Prof. Dr.	Perception, Communication, Architectural Design Process, Client, Virtual Reality	Mixed/Quantitative-Qualitative – Client Relationship and Virtual Reality	VR strengthens architect-client communication during design presentations, enabling better pre-construction evaluation and satisfaction.
Özel, B./2019/MS.c	ODTU/Asst. Prof. Dr.	Risk Recognition, Virtual Reality, Eye Tracking, Construction Site Safety	Mixed/Quantitative-Qualitative – Construction Site and Virtual Reality	Mobile VR, eye-tracking, and gamification improve construction workers' hazard recognition and safety awareness.
Dumlu, B./2018/MS.c	ITU/Asoc. Prof. Dr.	x	Mixed/Quantitative-Qualitative – User Experience and Virtual Reality	VR storytelling changes users' spatial perception and memory recall through audiovisual stimuli and virtual exploration.
Yıldan, İ./2018/MS.c	ITU/Prof. Dr.	x	Mixed/Quantitative-Qualitative – Virtual Education and Virtual Reality	VR environments foster creativity and flexible thinking in design studios, enhancing spatial perception compared to traditional 3D modeling.
Karışma, A./2017/MS.c	Gazi Uni./Asoc. Prof. Dr.	Architectural Design, Computer-Aided Design, Virtual Reality, Internet	Qualitative – Design and Virtual Reality	VR and IT applications increase efficiency in architecture and construction, yet knowledge gaps hinder fully interactive VR usage.

Author/Year/Thesis Type	University/Title	Keywords	Method/Theme	Finding
Aydın, E./2012/ PhD	YTU/Asst. Prof.Dr.	Virtual Reality, Three-Dimensional Virtual Reality, Representation, Architectural Representation, Semiotics, Dynamic Lighting	Mixed/Quantitative-Qualitative – Space and Virtual Reality	Dynamic lighting in 3D VR environments enhances spatial representation, but requires advanced interactive tools for full potential.
Kayapa, N./2011/PhD	YTU/Asst. Prof.Dr.	Virtual Reality Environment, Perceptual Differences Between Real and Virtual Reality Environments, Depth Perception, Visual Field, Visualization,	Mixed/Quantitative-Qualitative – Representation and Virtual Reality	VR expands spatial communication and design expression, with interactive visualization tools improving outcomes.
Töre, T./2010/MS.c	MSGSU/Prof. Dr.	x	Qualitative	VR is an effective tool for presenting and preserving cultural assets, supporting sustainability in conservation processes.
Ayoğlu, H./2005/MS.c	ODTU/Asst. Prof.Dr.	Digital Architecture, Extension of Reality, Virtual Reality Environment, Information Space	Qualitative	x
Zafer, D./2007/MS.c	Anadolu Uni./Assoc. Prof. Dr.	Architectural Design Process, Computer-Aided Design, Virtual Reality, Information Technologies, Virtual Reality Applications in Architectural Design	Qualitative	Integrating VR into architectural design strengthens communication and supports creative, collaborative solutions.
Kınayoğlu, G./2002/MS.c	ODTU/Assoc. Prof. Dr.	Depth, Virtual Reality Modeling Language (VRML), Computer-Based Architectural Representation	Qualitative	X
Ünur, K.2001/MS.c	YTU/Assoc. Prof. Dr.	Computer-Aided Design, Architectural Design, Virtual Reality, Virtual Reality-Aided Design, Technology	Qualitative	x
Karadayı, A./2000/PhD	KTU/Prof. Dr.	Architecture, Virtual Reality, Internet, Computer-Aided Design, CAD, Archive, Visual	Mixed/Quantitative-Qualitative	VR remains a virtual medium and can never fully replace the experience of real physical space.

Author/Year/Thesis Type	University/Title	Keywords	Method/Theme	Finding
		Model, Simulation, Multimedia		
Ünalı, C./1999/MS.c	İTÜ/Prof. Dr.	X	Qualitative	x

Evaluation of the Trends of Postgraduate Theses by Year

The chronological distribution of postgraduate theses on virtual reality (VR) in the field of architecture reflects the gradual yet notable integration of this technology into academic discourse in Turkey. Based on data obtained from the National Thesis Center (YÖK), the first master's thesis on VR was completed in 1999. Between 1999 and 2016, academic interest remained limited, with only one thesis produced in most years, and the research largely emerging from individual initiatives. The first doctoral dissertation was published in 2012, marking the initial shift from applied studies toward theoretical engagement with the topic.

A visible increase in interest has been observed since 2017. Although the number of theses remained modest at first, a steady upward trend became apparent after 2018. Notably, 2019 was the first year in which both a master's thesis and a doctoral dissertation were produced concurrently. Following a brief stagnation in 2020, a significant rise occurred in 2021 and 2022, with growing diversity in research themes and methodologies.

The most substantial increase took place in 2023 and peaked in 2024, with five and eleven theses completed respectively. While the majority of these studies were at the master's level, the presence of doctoral research has also become more consistent, reflecting a deepening academic engagement. These findings suggest that VR has evolved from a niche interest to a recognized and expanding research area in architectural scholarship.

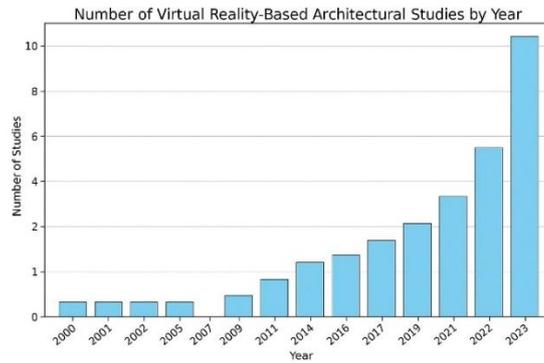


Figure 1. Architecture Theses on Virtual Reality by Year

Statistical Analysis of Postgraduate Theses by Academic Level

Within the scope of the 36 theses examined, the theme of virtual reality (VR) has been addressed specifically within the field of architecture. The vast majority of these theses are at the master's level; in total, 29 master's theses were identified, corresponding to 80.5% of the total sample. Doctoral dissertations, on the other hand, account for seven theses, representing 19.5% of the total. This distribution indicates that the topic of virtual reality in the discipline of architecture has primarily been explored at the master's level in the context of academic research.

The significant proportion of master's theses suggests that research in this area is still in its developmental and application-oriented phases, with a strong emphasis on examining the practical and implementation aspects of new technologies. The fact that studies on the use of virtual reality technologies in architectural education, design processes, and spatial perception are predominantly conducted at the master's level demonstrates that the experimental and applied dimensions of the field remain at the forefront.

On the other hand, although the proportion of doctoral dissertations is relatively low, these studies generally aim to make deeper theoretical and methodological contributions. Doctoral-level research investigates the conceptual dimensions of virtual reality technology within architecture—such as design paradigms, user experience, physical environment components, and educational models—in a more detailed and systematic manner, thereby contributing to the advancement of the discipline.

This distribution demonstrates that academic production on virtual reality in architecture is still on an upward trajectory; however, it also highlights the need for more advanced research and the development of theoretical frameworks at the doctoral level. Furthermore, the fact that both

master's and doctoral theses often employ mixed-method approaches—incorporating both qualitative and quantitative analyses—emphasizes the importance of interdisciplinary and multi-dimensional research perspectives in this field (Figure 1)

In conclusion, it can be observed that academic studies on virtual reality within the discipline of architecture are predominantly concentrated at the master's level; however, significant research is also being conducted at the doctoral level to deepen the field and strengthen its theoretical foundations. This situation indicates that, in parallel with technological developments, virtual reality applications in architecture will increasingly be addressed in a broader and more systematic manner.

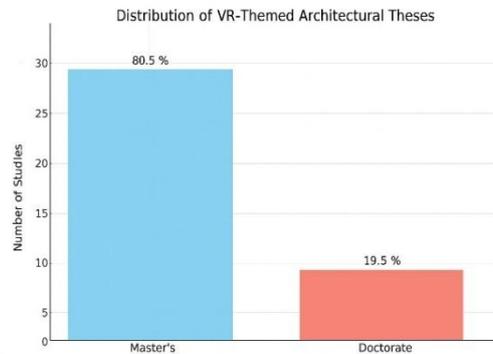


Figure 2. Distribution of Virtual Reality-Themed Theses in Architecture by Type

Analysis of Postgraduate Theses by Universities

The institutional distribution of VR-themed theses in architecture in Turkey reveals a strong concentration in technical universities located in metropolitan areas, particularly Istanbul. Istanbul Technical University (ITU) leads with nine theses, accounting for 25% of the total, reflecting its advanced research infrastructure and emphasis on technological innovation. Yıldız Technical University (YTU) and Middle East Technical University (METU) follow with three theses each (8.3%), underscoring their continued academic engagement in interdisciplinary research. Other Istanbul-based universities collectively contributed six theses (16.7%), highlighting the city's dynamic research environment.

In addition to metropolitan institutions, several regional universities such as Bursa Uludağ, Dumlupınar, Maltepe, Karatay, Balıkesir, Dokuz Eylül, Anadolu, İstanbul Aydın, Karadeniz Technical, and Kütahya Dumlupınar each produced one thesis (2.8%), indicating a nationwide

distribution. Konya Technical University and Gazi University, with two theses each (5.6%), also demonstrate notable regional contributions.

Overall, while VR research in architecture remains primarily centered in large technical universities, the participation of regional institutions suggests a growing national research landscape. This expanding academic interest indicates that future studies will likely become more diversified and widespread, supporting both innovation and international visibility in architectural education and technology.

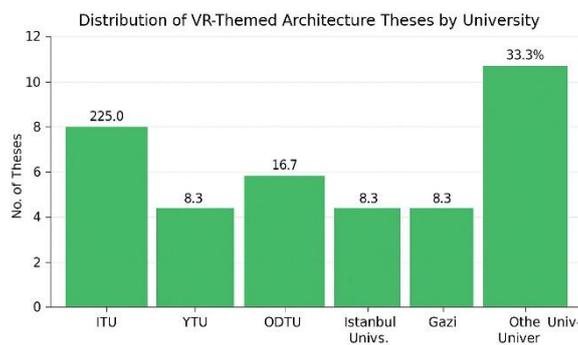


Figure 3. Distribution of Virtual Reality-Themed Architecture Theses by University

Analysis by Academic Title of Thesis Advisors

An evaluation of the academic titles of the advisors for the 36 theses examined provides significant insights into the level of academic supervision and the nature of the research produced. According to the data, the advisors' titles include Associate Professor (Assoc. Prof.), Assistant Professor (Asst. Prof.), Professor (Prof.), and, in some cases, supervisors whose titles are unspecified. This distribution offers valuable information regarding the academic experience levels of the advisors and the nature of the theses.

It is observed that for master's theses, advisors holding the titles of Associate Professor and Assistant Professor are more commonly involved. This suggests that master's students benefit from the guidance of experienced yet early- to mid-career academics during their research process. Advisors at the associate professor level or in the early stages of their academic careers after earning their PhD often play an active role in supervising research involving contemporary methodologies and technological innovations.

On the other hand, it is noteworthy that doctoral dissertations are more frequently supervised by academics holding the title of Professor. This can be attributed to the fact that doctoral studies require a higher level of expertise and guidance. The professor title reflects the academic's extensive experience and scholarly productivity, making it expected for doctoral students to work under the mentorship of senior scholars at this level.

Additionally, the fact that some theses do not specify the advisor's title, or that this information is unclear, indicates certain gaps in data records, which slightly limits the precision of the analysis.

Overall, when viewed in terms of advisor titles, it can be said that virtual reality-themed theses in architecture—at both the master's and doctoral levels—are supervised by experienced academics. This plays an important role in ensuring the scientific rigor and quality of the research produced.

In conclusion, the distribution of academic advisor titles demonstrates that academic production in the field of architecture and virtual reality in Turkey is supported by scholars at various stages of their academic careers, and that interdisciplinary knowledge is being transferred to emerging researchers. This diversity enables research in the field to advance on a foundation that is both innovative and robust (Figure 4).

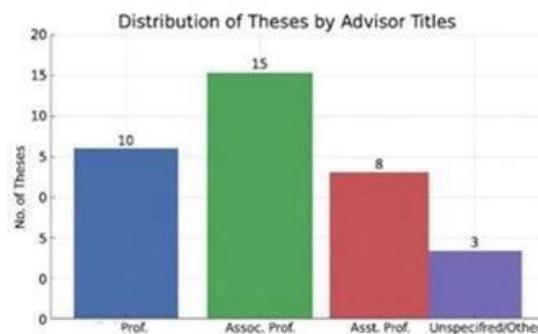


Figure 4. Visualization of the Relationship Between Advisors' Academic Titles and the Number of Postgraduate Theses

Analysis of Keywords

The table of 36 postgraduate theses includes a variety of keywords associated with virtual reality (VR) and architecture. These keywords reflect the thematic focuses, methodologies, and application areas of the theses, providing an important framework for understanding how VR is utilized within the discipline of architecture. Below, the frequency of keywords, their thematic groupings, and their relationships with the theses are analyzed.

Frequency Analysis of Keywords

An examination of the keywords shows that certain terms are frequently repeated, highlighting specific thematic focuses. The most commonly used keywords and their frequencies are listed below (note that some theses do not specify any keywords):

Virtual Reality (VR): Appears as a common keyword in all 36 theses, serving as the central focus for all studies.

Spatial Perception: Directly indicated in five theses [5,19,24,16,1] and addressed indirectly in others.

Architectural Education: Specified as a keyword in five theses [3,19,4,21,16].

- **Urban Design:** Clearly mentioned in two theses [10,11]
- **Cultural Heritage:** Highlighted in two theses [7,6]
- **Wayfinding:** Used as a keyword in two theses [8,9]
- **Interior Architecture:** Specified in two theses [3,19]
- **Design Process:** Found in three theses [21,2,36]
- **Other Notable Keywords:** Terms such as Augmented Reality (AR), Construction Site Safety, Biophilic Design, Neuro-Architecture, E-commerce, Gaming, and Spatial Representation each appear once and reflect more specific themes.

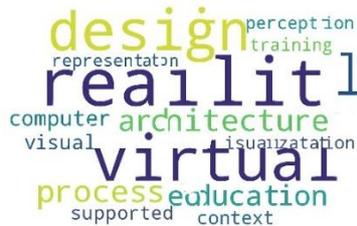


Figure 5. Word Cloud Analysis of Keywords in Postgraduate Theses

Analysis of Research Methods Used

The total of 36 theses examined were classified into three main categories based on their methodological approach: qualitative, quantitative, and mixed-method (qualitative + quantitative).

• Theses Using a Qualitative Method:

A total of nine theses (25%) relied solely on qualitative research methods. These studies predominantly employed techniques such as observation, content analysis, thematic analysis, and experiential reflection. Theses in this group often focus on topics such as architectural representation, user experience, and the design process.

• Theses Using a Quantitative Method:

Four theses (11.1%) used only quantitative data, concentrating on tools such as surveys, statistical analyses, and numerical performance measurements. Although this group is more limited in number, it appears particularly in studies involving data-driven modeling and user testing.

• Theses Using a Mixed-Method Approach:

The majority of the theses—23 in total (63.9%)—were prepared using a mixed-method approach. In these studies, qualitative and quantitative techniques are integrated: user opinions related to VR experiences are supported by statistical analyses, while thematic content is enriched through observation and interpretation.

The data show that the most commonly used research method in VR-themed architecture theses is the mixed-method approach. This indicates the necessity of evaluating a multidimensional technology like VR in a way that considers both user experience and measurable outcomes. On the other hand, the fact that qualitative methods are preferred more frequently than purely quantitative ones aligns with the experiential, visual, and interpretive nature of the discipline (Figure 6)

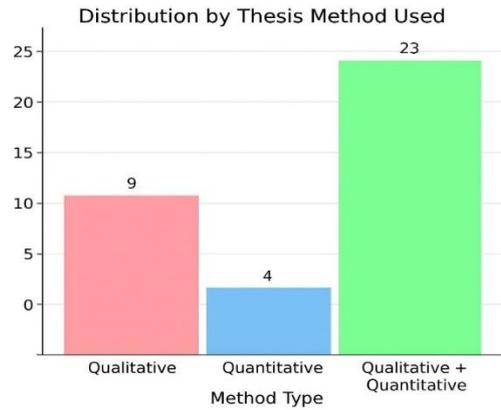


Figure 6. Distribution of Research Methods Used in Postgraduate Architecture Theses

Analysis of Thesis Findings

When the general findings of the theses are evaluated thematically, it becomes evident that virtual reality (VR) technology provides multifaceted contributions to the discipline of architecture. Many studies have demonstrated that VR technology enhances users' understanding, perception, and experience of space, proving especially effective in clarifying complex spatial organizations, abstract design ideas, and wayfinding processes. In education-focused theses, VR has been defined as a tool that increases students' creativity, spatial awareness, motivation, and engagement, and has been shown to deliver more effective learning outcomes compared to traditional methods in fundamental design, interior design studios, and construction knowledge courses.

In user experience and interaction-based studies, it is noted that the interactive environments provided by VR increase user satisfaction and strengthen the client-architect relationship during architectural presentations. Theses focusing on architectural design processes indicate that VR particularly expands diversity during the conceptual design stages, supports intuitive decision-making, and contributes to collaborative processes. In the context of urban design and cultural heritage, VR emerges as a tool that enhances public participation, enables the digital presentation of cultural heritage, and strengthens awareness of preservation.

Studies related to wayfinding behavior and emergency scenarios reveal that VR offers a robust simulation environment that allows for the objective analysis of user behaviors. Findings on sectoral applications indicate that VR accelerates work processes in fields such as construction, shopping, and construction site safety, increases risk awareness, and improves the consumer

experience. In this respect, VR technology can be considered a transformative tool in the field of architecture at both pedagogical and practical levels.

Evaluation of Findings in Terms of Research Depth and Conceptual Framework

Doctoral dissertations are generally built upon a more comprehensive theoretical background and aim to provide advanced contributions, such as developing design criteria, proposing models, or suggesting pedagogical frameworks.

- For example, [18] proposed a design guide for virtual learning environments.
- Doctoral theses such as [4] and [16] developed teaching models, pedagogical strategies, or assessment tools.

Master's theses, on the other hand, have mostly focused on identifying the current situation, conducting situational analyses, investigating user perception, exploring technological integration, or implementing small-scale experimental applications.

- For instance, [19] examined the impact of VR on color and material selection,
- While [10] analyzed potential future trends but did not produce a model.

Depth of Findings in Relation to Research Methods

- All doctoral dissertations (100%) employed a mixed-method (qualitative + quantitative) approach. This method combines user experiences with statistical analyses, resulting in multidimensional findings.

- In master's theses, the distribution was approximately: mixed-method (62%), qualitative only (21%), and quantitative only (17%). This indicates that while doctoral theses tend to achieve greater research depth, master's theses generally work with more limited data sets.

Thematic Analysis of Postgraduate Theses

Based on the data presented in the table, the thematic analysis shows that the concept of virtual reality (VR) has been addressed from various perspectives, particularly in the fields of architecture, interior architecture, urban design, education, the construction industry, and cultural heritage. Among the theses examined, the most frequently recurring themes include VR-supported educational environments, the design process, spatial perception, representation and visualization, urban design, cultural heritage, and safety. Notably, the greatest concentration is observed in VR-based educational applications. The studies emphasize the potential of VR technology to enhance student engagement, strengthen spatial perception, foster creative thinking, and contribute innovatively to core design pedagogy within interior architecture and architectural education. In this regard, VR applications are highlighted as

effective tools for increasing learning motivation and interaction among Generation Z students and for concretizing abstract concepts.

Similarly, in relation to the design process and spatial perception, the use of VR has been discussed in terms of enriching user experience, improving the comprehensibility of complex spaces, and offering new possibilities for representation through the transfer of physical environmental components into virtual settings. In the themes of representation and visualization, it is emphasized that elements such as photorealistic or non-photorealistic visualization techniques, dynamic lighting, and perceptual depth enhance architectural communication and that interactive presentation techniques contribute to the evaluation of design decisions.

In the context of urban design, VR technologies support user participation and community engagement, thereby contributing to making urban spaces more comprehensible and accessible. Topics such as urban space simulations, neuro-architectural approaches, and user experience illustrate the concentration of research in this area. Additionally, in the domains of cultural heritage and historical environment conservation, innovative approaches such as the digital presentation of historic structures, VR integration, multilingual support, and AI-assisted personalization have demonstrated the potential for strengthening public awareness of historic environments and increasing conservation consciousness.

On the other hand, in the construction industry and construction site safety themes, aspects such as risk recognition, eye tracking, and smart construction have been discussed in relation to the applicability of VR in occupational safety training. Furthermore, in more specific areas such as wayfinding behavior in healthcare facilities, emergency evacuation scenarios, and the relationship between gaming and space, VR applications have been shown to enable detailed and objective analysis of user behaviors.

Overall, these themes indicate that VR technologies are strongly integrated with concepts such as spatial perception, user experience, participation, representation, design processes, safety, and conservation within architecture and related fields, with a particular focus on educational processes. Accordingly, the contributions of VR applications—such as enhancing interaction, concretizing design decisions, and fostering user-centered design approaches—are prominent; however, it is also understood that limiting factors such as technical challenges, costs, and user habits must be taken into account(Figure 7)

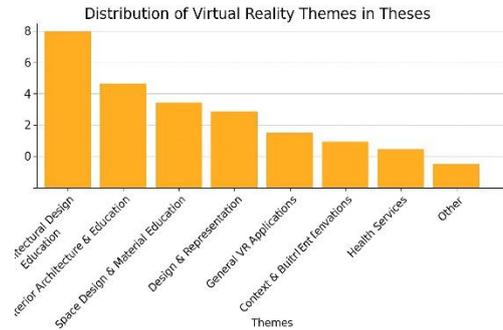


Figure 7. Thematic Concentrations of Virtual Reality in Theses

Findings

Findings on Trends of Postgraduate Theses by Year

The distribution of theses by year shows a significant increase in virtual reality (VR)-themed research, particularly in the last five years. This growth is thought to be related to the spatial constraints experienced during the pandemic and the increased need for remote education models. In addition, improved accessibility to hardware and software has likely contributed to this rising interest. The limited number of theses produced in the early years (1999–2016) can be explained by the fact that VR technologies were not yet widespread and technical infrastructure was limited at that time. The peak in the number of theses in 2024 suggests that the practical value of VR within the discipline of architecture has become more widely recognized.

These findings indicate that VR technology is becoming increasingly institutionalized in academia and holds development potential both in practical and theoretical dimensions.

Findings on the Academic Levels of Postgraduate Theses

The fact that the majority of theses have been produced at the master's level suggests that the topic of VR in architecture is still largely in an exploratory and application-oriented phase. This is thought to be due to the practical nature of VR technologies, which are well-suited for producing outputs based on real-world applications, thus driving research to be predominantly experimental and project-based. The relatively small number of doctoral dissertations implies that the theoretical foundations of the subject are not yet fully mature, although they are beginning to deepen. This difference can be attributed to the fact that master's theses tend to test the applicability of new technologies, while doctoral research aims to develop conceptual models and establish methodological frameworks that make more advanced contributions.

Overall, these findings suggest that VR-focused research in architecture is primarily embraced as an applied field but is also beginning to strengthen its potential for theoretical development.

Findings on Universities Producing Postgraduate Theses

In the distribution of theses by university, Istanbul Technical University (ITU) clearly leads, which is thought to be due to the institution's strong infrastructure in architecture and digital technologies and the high level of academic interest in the topic. Similarly, Yıldız Technical University (YTU) and Middle East Technical University (METU) are also seen to support innovative themes like VR through their well-established engineering and architecture faculties. The notable contributions from other Istanbul-based universities are linked to the city's expansive academic network and technological ecosystem. This concentration is believed to result from the robust research infrastructure, laboratory facilities, and interdisciplinary collaborations available in major cities. Meanwhile, the representation of universities across Anatolia—even at lower percentages—indicates that the subject is not limited to metropolitan institutions and that awareness is increasing nationwide. The contributions of mid-sized technical universities (e.g., Gazi University, Konya Technical University) are seen as signs of growing local academic interest in VR.

In conclusion, these findings suggest that the concentration of VR-focused architecture theses at large urban universities with strong infrastructures is expected, yet regional diversity is also expanding.

Findings on Advisors' Academic Titles

An examination of advisor title distribution shows that associate professors and assistant professors are more commonly involved in supervising master's theses, whereas professors tend to supervise doctoral dissertations. This is thought to reflect the need for more hands-on supervision by younger, dynamic academics for current, technology-focused and practice-based master's research. Conversely, the advanced theoretical frameworks and methodological rigor required at the doctoral level necessitate the guidance of more senior academics. These findings suggest that in a new research area like VR, knowledge transfer is balanced between younger and more experienced academics. Instances where advisor titles are missing or unclear likely stem from inconsistencies in record-keeping, which can limit the reliability of the data to some extent. Overall, this pattern indicates that the diversity of academic supervision plays an important role in supporting interdisciplinary knowledge sharing within VR-themed architecture research.

Findings on Keywords

The keyword analysis shows that spatial perception, architectural education, and urban design/cultural heritage are the dominant themes in VR-focused architecture theses. This is thought to be related to VR's potential to enhance spatial experience, increase interaction in education, and support participatory design processes. The fact that master's theses include more practice-oriented, specific themes (e.g., wayfinding, construction site safety) is likely due to students' need to test VR in tangible contexts. Conversely, the more abstract, conceptual, and innovative keywords found in doctoral theses align with the need to strengthen the field's theoretical framework. The absence or vagueness of keywords in some theses is thought to result from a lack of attention during data recording and classification, partially limiting the depth of the analysis. Overall, the diversity and thematic clustering of keywords demonstrate that VR is embraced as an interdisciplinary exploration field within architecture.

5. DISCUSSION AND RESULT (TARTIŞMA VE SONUÇ)

The findings of this study indicate that the application of virtual reality (VR) technology within the field of architecture is primarily concentrated in domains such as educational processes, spatial perception, representation, and urban design. This trend appears to arise from the necessity of concretizing conceptual abstractions inherent in design-based disciplines, as well as from the interaction expectations characteristic of Generation Z students. However, the data also reveal that VR has been comparatively underexplored in more practical areas, including the construction sector, construction site safety, and wayfinding behaviors. This suggests that the practical dimensions of the technology remain somewhat limited and warrant further investigation.

Another significant point emerging from the study pertains to the insufficient attention given in the theses to limiting factors such as cost, inadequate technical infrastructure, and user habits. This observation underscores the need for a more thorough theoretical examination of the fundamental barriers impeding the broader adoption of VR applications. While the widespread use of mixed-method approaches in the reviewed theses reflects a commendable methodological richness in capturing the multifaceted effects of VR, it is anticipated that this approach could be further strengthened through the inclusion of detailed, in-depth case studies.

In the analyzed theses, the contributions of VR technology to architectural practice are generally presented within a positive framework, positioning the technology as a tool that enriches spatial experience and facilitates the design process. Nevertheless, this perspective often overlooks

critical arguments suggesting that VR may offer a superficial mode of representation, weaken connections with physical space, and overshadow the intuitive dimensions of design. Contrasting viewpoints in the literature contend that VR has the potential to reduce architectural thinking to a predominantly digital paradigm. Consequently, there is a clear need for a heightened level of critical evaluation in the theses, allowing for a more comprehensive exploration of the technology's potential limitations and contentious aspects.

Although VR technology is often lauded in the literature for its capacity to support innovative design processes and enhance spatial experiences, opposing perspectives also exist. Certain scholars argue that VR reduces architectural thought to digital representation, undermining the sensory and intuitive connections with physical space. Furthermore, critiques suggest that the technology may instrumentalize the design process, potentially diminishing the creative role of the architect. In this context, the impact of VR on architectural practice should be assessed not only in terms of its potential benefits but also through a critical lens that acknowledges its possible drawbacks.

In conclusion, this study emphasizes the opportunities offered by VR technologies in architectural practice, education, and design processes, while simultaneously highlighting the need to strengthen interdisciplinary collaborations, broaden practice-oriented research themes, and maintain methodological diversity. Future research is expected to address both the theoretical and practical boundaries of VR in a more holistic manner, thereby uncovering the true potential of the technology within the field of architecture.

6. RESULTS (SONUÇLAR)

This study provides a comprehensive analysis of master's and doctoral theses focusing on virtual reality (VR) within the discipline of architecture in Turkey, revealing both methodological and thematic trends. The analysis demonstrates that VR is predominantly addressed in contexts such as education, spatial perception, representation and visualization, urban design, cultural heritage, and safety. This emphasis is likely rooted in VR's multifaceted contributions, including its capacity to enhance spatial understanding, concretize abstract concepts, increase student engagement, and support design processes. The findings further indicate that the vast majority of these theses are at the master's level, suggesting that VR research in Turkey remains largely practice-oriented, experimental, and user-centered, whereas more comprehensive theoretical frameworks are primarily developed at the doctoral level.

The prevalence of the mixed-method approach as the most frequently employed research strategy underscores the necessity of evaluating an interactive technology like VR through both qualitative and quantitative lenses. Additionally, the dominance of Istanbul-based technical universities in the institutional distribution points to the critical role of strong academic infrastructure and advanced technological resources in supporting research output in this field. While VR technology is gaining visibility in architectural research in Turkey, the study identifies several methodological and thematic gaps. In particular, technical barriers, costs, user habits, and sustainable integration are insufficiently addressed, which represents a significant limitation for the long-term adoption of VR applications in architectural practice.

Looking forward, it is recommended that VR-focused architectural research move beyond purely application-oriented studies and develop interdisciplinary approaches capable of deepening the theoretical framework. Comprehensive doctoral-level investigations, including modeling, the development of evaluation criteria, and pedagogical strategy proposals, would strengthen the knowledge base and provide a foundation for innovative applications. Moreover, expanding the use of VR in areas such as the construction sector, construction site safety, risk management, and smart building design could accelerate the integration of this technology into practical, real-world contexts.

In the context of Turkish master's and doctoral theses, VR integration in architecture is predominantly examined within educational and representational frameworks. While this approach exhibits certain parallels with international literature, it provides a comparatively limited discussion of epistemological and ethical dimensions. For instance, academic studies in North America and Western Europe more frequently explore VR's potential to transform authority relationships within the design process, the implications of user-centered design paradigms, and the ontological status of digital space. In Turkey, such theoretical expansions are still in a developmental phase. This observation is important for assessing the extent to which local academic production aligns with global trends and where it diverges.

VR's position within the discipline of architecture should be considered not merely as a technical tool but as a phenomenon that transforms knowledge production processes, professional ethical values, and institutional structures. Within this framework, it can be argued that VR generates an epistemological shift in architecture, redefining the experience of space along the axis of digitalization and altering the subject-object relationship in the design process. Foucault's theoretical framework on knowledge-power relations and the production of space offers a valuable reference point for understanding VR's effects on architectural representation. Additionally, the ethical dimensions of VR can be discussed in relation to the processing of user data, the privacy of digital space, and the democratization of design. At the institutional

level, VR is observed to redefine professional roles, transform collaborative models, and reshape professional standards in line with digitalization.

In conclusion, this study demonstrates that VR holds considerable potential within architecture, particularly in pedagogical, design, and representational contexts. To fully harness this potential, it is essential to strengthen interdisciplinary collaboration at the postgraduate level, maintain methodological diversity, and support practice-based projects in partnership with sector stakeholders. Such an approach would facilitate the integration of VR into architectural practice in a more qualified, sustainable, and enduring manner, enhancing spatial perception, user experience, and design processes.

DECLARATION OF CONFLICT OF INTEREST

The author declares that no potential conflict of interest or financial benefit has arisen in relation to this study

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