Factors Impacting Resilience of Internet of Things Systems in Critical Infrastructure

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Abstract—Internet of Things (IoT) systems are recently being employed in various types of critical infrastructure, including integrated rescue systems, healthcare, defence, energy and other fields. Recently, the security and safety of IoT systems, in general, has been questioned by a number of studies. Raised concerns do not relate to the IoT technology in principle but to poor engineering practices that are mostly preventable. In critical infrastructure, demand for safety and security is strongly present and justifies a discussion about the general resilience of IoT systems. In this context, resilience includes system resistance to cyberattacks and its stability to operating conditions and system reliability and safety in terms of present flaws. In this paper, we discuss relevant factors impacting the resilience of IoT systems in the critical infrastructure and suggest possible countermeasures and actions mitigate the potential effects of these factors. Contrary to the previous work, an unique critical system Model-based Testing viewpoint is taken in this analysis.

Index Terms—Internet of Things, resilience, safety, reliability, quality, testing, interoperability, security, critical systems, critical infrastructure

I. INTRODUCTION

Currently, Internet of Things (IoT) systems are being employed as integral parts of a number of work processes, where manufacturing, healthcare, energy, transportation or critical infrastructure are just a few examples [1], [2]. This paper focuses on Critical Infrastructure (CI), in which the low resilience of employed IoT systems might have severe consequences. As CI, we consider healthcare, energy, integrated rescue system, defence, logistics of medical material or material reserves and other systems that support essential processes, whose disruption may cause severe harm on lives, health, national security or significant material loss[1]. In this paper, we discuss IoT system resilience as a complex quality that allows the system “to return to normal condition after the occurrence of an event that disrupts its state” [3]. Individual reviews have been conducted on resilience definitions and measures in different systems and domains, including technological systems [3], [4]. Also, some recent studies analyze this concept in the context of IoT technology, usually focusing on selected aspects of the system [5]–[7]. A recent paper by Berger et al. provides the most comprehensive viewpoint here [9], focusing on taxonomy, inventorying individual aspects of the system to be included in the resilience category and suggesting a set of possible metrics.

However, no study has taken an approach to analyze factors impacting system resilience from the critical system testing viewpoint to suggest actions or countermeasures that can be used to mitigate their possible impact. In contrast to the previous works, this study does not discuss general IoT quality aspects but starts the analysis of issues and mechanisms behind the possible weak resilience. The critical system testing approach taken from the model-based testing (MBT) discipline viewpoint is taken.

Considering the extent of the current employment of IoT in CI and its growth, this comprehensive discussion dedicated to the general resilience of implemented IoT solutions is desired - especially in the situation when the critical system testing aspect has not been adequately addressed yet. To this end, we believe the analysis as given in this paper will be useful for IoT researchers, industry engineers and policymakers.

The paper is organized as follows. Section [II] summarizes related work. Section [III] discussed factors impacting IoT system resilience from MBT perspective. Section [IV] discusses...
possible countermeasures and actions to be taken to lower the possible effects of analyzed factors in general terms. The last section concludes the paper.

II. RELATED WORK

As a consequence of the current IoT market size, numerous studies have been published discussing individual aspects of IoT system testing, reliability and security. Security and privacy is a major subject of challenge reports [9]–[12] to give few. The reports explain the overall principles behind possible poor security of IoT systems, e.g. [10], [11], or list particular security flaws, e.g. [12]–[14].

Reliability and quality assurance topics have been also addressed by previous reports [9], [15]–[17]. In the reports on testing topic, challenges in interoperability and integration testing are frequently mentioned [9], [15], [17]–[19].

Generally, much fewer works exist directly discussing these challenges in the context of CI systems. In the field of security, recent cyberattacks on CI have been analyzed in some studies [13], [14] or general security threats were discussed [20], [21].

However, regarding reliability, testing and quality assurance challenges for CI IoT systems specifically, it is difficult to find a study that addressed this topic directly. CI domain is naturally included in previous reports on this topic, either explicitly or implicitly [9], [15], [16], but quality assurance challenges, in general, might naturally differ from a non-critical consumer IoT system to a critical system in CI. Hence a unified view on IoT testing is not helpful, and CI IoT systems have been analyzed separately from this viewpoint.

Considering the resilience concept itself, the definition of the concept among various fields, including technology, has been a subject of individual reviews [3], [4]. In the context of IoT, individual studies usually focus on resilience system-specific aspects. For example, employing blockchain to increase the resilience of data handled by system [7], the resilience of the system against edge-induced cascade-of-failures [6] or resilience against network outages [5] can be given. Works taking a more holistic approach to IoT resilience are also available [8], [22], of which a survey by Berger et al. is the most comprehensive one. The survey focuses on resilience taxonomy and term definition. Then it lists system quality aspects that have to be included in the resilience concept and suggests some metrics to measure the resilience as a system quality [8].

However, no study so far has addressed the resilience concept directly from the critical systems testing viewpoint, where, instead of general quality characteristics, technical properties and details of a system are analyzed, and possible countermeasures are suggested. Moreover, no recent work discusses the resilience concept in the context of MBT methods, essential to maintain the required level of reliability for the IoT systems employed in CI. This approach is the subject of this paper.

A. Principal areas

In our proposal, we reflect on four principal areas impacting the resilience of IoT systems in CI. Deliberately, security aspects are not separated from functional correctness or interoperability aspects, as a unified view opens the room for more effectiveness of the MBT methods when employed in the IoT system.

Complexity. In general, the complexity of systems is constantly growing, and the IoT world is not an exception. More complex systems are more prone to failures, which can be well documented by a relation of level of interactions among individual system parameters and effort needed to guarantee a certain level of reliability [23]. Critical systems are empirically observed as having a lower level of this combinatorial complexity [23], which is due to good coding and engineering practices. However, the growing system complexity issue in general naturally impacts the CI domain regardless of engineering practices.

Attack surface. Security and data privacy are some of the most discussed issues in current IoT technology [9], [24]. Many factors might be a source of weak security of IoT systems and increase its attack surface. These factors start from poor security of end devices and end by security flaws in the communication infrastructure, or back-end parts of the systems [10], [11]. Solar or battery-based energy supply in end devices might lead to neglection of security procedures in device firmware, as economic power consumption is needed and more complex computations cannot be afforded. This issue connected with the low ability to update the firmware online and placement of the devices in locations with difficult access to inspect is making the devices the ideal target for cyber-attackers. Also, the employment of universal hardware building blocks for end devices might emphasize the problem: the attack surface of such a universal bloc is usually higher than it would be for proprietary hardware built only for a particular purpose. Considering the rule "the
system is strong as its weakest part\(^2\), the attack surface of an IoT system employing weakly secured devices might be alarmingly high\(^1\)–\(^3\).

Other issues relate to used communication infrastructure and back-end parts of an IoT system. If the infrastructure is not properly updated, zero-day security flaws or known security vulnerabilities add on a potential attack surface that an attacker might exploit. Technological heterogeneity, if present in the system, might contribute to the problem as another factor\(^2\).

**Heterogeneity.** Variety of protocols is usually employed in IoT systems. Part of these protocols are standard, and part of them are pure proprietary, and their mixture in one solution causes a number of interoperability challenges\(^2\). Sometimes, device producers make the issue worse by possible intentional vendor lockout. Recent IoT standardization initiatives attempt to improve this situation\(^2\) for instance, Internet of Things Global Standards Initiative\(^3\) or IoT standardization initiative by European Telecommunications Standards Institute (ETSI)\(^3\). However, the process is ongoing, and standardization is overrun by the necessity to implement various IoT solutions in the industry praxis.

**Interoperability.** Due to lower standardization level and poor engineering practices during system creation, combined with the employment of universal end devices and infrastructural parts by various producers, interoperability of system individual parts might be problematic. In expected scenarios of system operation, interoperability is usually verified by integration tests. However, when unexpected edge conditions are activated during system operation, integration and interoperability flaws might activate and put safe system operation to risk.

**Unknown system parts.** When employing reusable IoT building blocks with larger functionality that is essential for an IoT system in CI, unused parts of the functionality of these blocks can be left out of the scope of created documentation and test plans. Possible attack surface might be not documented, and if triggered by some flaw in documented part of the system, unused parts might be a source of unexpected system behaviour. Such parts are an especial challenge for MBT, as they stay aside from the system models. Hence the created tests do not cover them.

**Automated testability.** IoT systems employed in CI are typical of mission-critical nature, and thoroughness of tests has to be typically high to ensure required reliability and safety. Hence, MBT-based test automation is essential to ensure the required level of test coverage. Consequently, the feasibility of creating automated tests for individual parts of the system is an important issue that directly impacts created test strategy. Previous works report on automated testability of web applications\(^27\), \(^28\) and also support this process\(^29\) and these can also be utilized for web-based user interfaces of IoT systems. However, this issue relates to lower system levels and integration tests and has to be taken into account in project design phases.

**Factors potentially impacting resilience and their relevance to principal MBT techniques**

In the following overview, we first identify factors that can impact the resilience of IoT systems used in CI and, concurrently, are relevant from the MBT viewpoint. Regarding the selection of factors, we selected system properties that typically (1) impact the input system model for MBT and (2) have an impact on low-level test strategy determination, which includes a selection of testing techniques, test coverage criteria or prioritization of system parts to test. This overview is given in Table \(\text{I}\) and is provided for each of the principal areas given in Section \(\text{III-A}\).

Some factors duplicate for individual principal areas and have to be further considered in the context of these areas, as principal MBT techniques that can be applied might differ by this context.

In the second part, we position the factors identified in Table \(\text{I}\) to principal MBT techniques. The selection of these techniques is a subset of numerous generally discussed approaches and techniques in MBT\(^31\)–\(^33\) and bases on selection in TMAP Next industrial methodology\(^34\) which recently focused on IoT systems\(^35\). The mapping is presented in Table \(\text{II}\).

A the principal MBT techniques, we identified Constrained interaction testing (being the current common successor of the Combinatorial interaction testing discipline), Path-based testing also known under industrial synonyms as workflow testing or process testing. State machine testing having certain overlap with path-based testing, but being interpreted as standalone discipline, Data-flow testing which includes special data consistency tests based on CRUD matrices as well as code-level data-flow testing employing control-flow graphs, and, finally, logic-coverage techniques handling more low-level elements in the test design\(^31\)–\(^34\).

The typical relevance of the principal MBT technique to discussed factor is expressed by “X” mark in the table. In
| Principal area | Factor | Description |
|---------------|--------|-------------|
| Complexity    | Interaction among parameters | Extent to which individual parameters in the system interact together [23] |
|               | Number of modules | Number of individual modules that are communicating by internal or external interfaces |
|               | System size | Size of the whole system expressed in lines of code, use cases, number of functions or other means |
|               | Internal code complexity | Complexity of internal procedures, for which established code metrics [30] can be used |
|               | Data model size | Complexity of data model in principal data objects and their relations in a persistent data storage layer |
|               | Internal and external interfaces | Number and complexity of internal and external interfaces |
| Attack surface | Device types | Number of individual types of device used in the system and their versions |
|               | Communication protocols | Number of communication protocols used in the system and differences in their types |
|               | External interfaces and endpoints | Number and complexity of external interfaces and endpoints, also considering used communication protocol and its security |
|               | Commonly known vulnerabilities | Number and types of commonly known vulnerabilities in employed devices and infrastructural part of the system |
|               | Security antipatterns | Identification of system parts containing security antipatterns and their density |
| Heterogenity  | Programming languages | Number of used programming languages and differences in their nature (low-level vs. high-level) |
|               | Communication protocols | Number of communication protocols used in the system and differences in their types |
|               | Device types | Number of individual types of device used in the system and their versions |
| Interoperability | Internal and external interfaces | Number and complexity of internal and external integration interfaces |
|               | System configurations | Number of possible system configurations (versions and types of devices, versions of software modules) |
|               | Runtime scalability | Extent to which system configurations can change during system operation |
| Unknown system parts | Universal devices | Number of devices having more broad functionality than used in system processes |
|               | Third-party code | Density of external source code (third-party or open-source) that is not directly employed in system processes |
|               | Universal interfaces | Number and types of system interfaces created from reusable building code blocks that are not directly employed in system processes |
| Automated testability | Testability of user interfaces | Extent to which parts of system user interfaces are accessible for automated tests |
|               | Testability of integration interfaces | Extent to which system integration interfaces can be accessed by automated tests |

specific cases, situations extending this relevance to more principal MBT techniques might occur.

IV. DISCUSSION AND FUTURE DIRECTIONS

Numerous factors can contribute to the increased resilience of IoT systems [8]. From the specific MBT viewpoint, these factors can be divided into the following principal categories: (1) education of IoT engineers to create a more resilient system by design, (2) development of more effective testing methods to ensure resilience, and (3) more intensive standardization activities in the field.

Regarding system design and enhancement of current engineering practices, two areas are relevant in this point. First, the design of an IoT system itself impacts resilience. Numerous factors are influencing system resilience, and those directly related to the MBT viewpoint are listed in Table I. Generally, the system’s compact design contributes to a lower attack surface. Unnecessary internal complexity increases the probability of flaws and defects left undetected during testing phases. Security and privacy by design are paradigms that have to be employed. These factors when designing a CI system contribute to higher system resilience. The second aspect is creating a well testable system, especially by automated tests. Such a praxis allows for successful detection of relevant defects in the system before its roll out to a live operation.

Another direction that can effectively work in synergy with the previous one is the development of more effective testing methods specifically focused on IoT systems. From the major MBT streams discussed in this paper (See Table II), combinatorial and constrained interaction testing seems quite sufficient for the case, as well as path-based testing in general. However, more focus has to be dedicated to specific testing of IoT interoperability, and integration issues, as well as edge conditions in an IoT system, might operate (e.g. disrupted parts of distributed infrastructure, outage of particular devices or network connectivity) [9].

The last main direction to recommend is stronger stan-
TABLE II
Mapping of the factors having potential impact on IoT system resilience to principal MBT techniques.

| Principal area impacting IoT resilience | Factor impacting IoT resilience | Typical relevance to principal MBT techniques |
|----------------------------------------|--------------------------------|-----------------------------------------------|
| Complexity                             | Interaction among parameters  | x                                              |
| Number of modules                      | x                               |
| System size                            | x                               |
| Internal code complexity                | x                               |
| Data model size                        | x                               |
| Internal and external interfaces       | x                               |
| Attack surface                         | x                               |
| Heterogeneity                          | Programming languages           | x                                              |
| Communication protocols                | x                               |
| Device types                           | x                               |
| Internal and external interfaces       | x                               |
| System configurations                  | x                               |
| Interoperability                       | Runtime scalability             | x                                              |
| Unknown system parts                   | Universal devices               | x                                             |
|                                      | Third-party code                | x                                             |
|                                      | Universal interfaces            | x                                             |
| Automated testability                  | Testability of user interfaces  | x                                             |
|                                      | Testability of integration interfaces | x   |

In this paper, we analyzed the resilience of IoT systems from a specific MBT-viewpoint, an approach that has not been taken in previous studies to the resilience topic. This viewpoint concentrates on the critical system testing process in which the employment of MBT-based test automation is a natural and inevitable tool. Hence, it extends the analyses provided in the current literature by a highly practical viewpoint that has to be reflected during IoT projects in CI.

Provided view focuses on factors directly impacting MBT test strategy and test design process. It covers principal areas of system complexity, attack surface size, technological heterogeneity, interoperability factors, the presence of unknown system parts, and the extent to which the system can be handled by automated tests that are essential for testing of mission-critical systems in CI.

As no previous study directly addressed an overview of the main issues from a general quality assurance viewpoint and specifically for CI systems, we provided such an overview in this paper. As issues, security, interoperability, heterogeneity and complexity were included, followed by more general issues as impact of the competitive environment and growing reliance on IoT systems.

V. CONCLUSION

The extent of IoT systems employed in various domains of people activity constantly grows, and the CI field is not an exception. In contrast to IoT systems in typically non-critical domains as entertainment, smart home or retail logistics, usage of IoT technology in CI amplifies the significance of issues and challenges threatening security, safety and reliability of the systems. These factors have to be kept in mind from the beginning of CI system design, and development and countermeasures have to be taken to mitigate their possible effect.

In this paper, we analyzed the resilience of IoT systems from a specific MBT-viewpoint, an approach that has not been taken in previous studies to the resilience topic. This viewpoint concentrates on the critical system testing process in which the employment of MBT-based test automation is a natural and inevitable tool. Hence, it extends the analyses provided in the current literature by a highly practical viewpoint that has to be reflected during IoT projects in CI.

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