MODELING AND DEBUGGING OF MEASUREMENT DATA PROCESSING ALGORITHMS

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Аннотация. Представлен подход к верификации и отладке алгоритмов обработки измерительной информации в системах, использующих архитектуры Edge и Fog вычислений. На практическом примере продемонстрировано поведение измеряемых параметров при возникновении ошибок на различных уровнях распределённой обработки данных — на периферийных (Edge) устройствах и промежуточных узлах (Fog). Показано влияние задержек, частичной потери данных и некорректной предобработки сигналов на итоговые результаты измерений в реальном времени. Продемонстрированы методы выявления и локализации ошибок с использованием формальных математических инструментов, в частности сетей Петри, позволяющих моделировать распределённые вычислительные процессы. Рассмотрены основные типы ошибок, возникающих в условиях децентрализованной обработки, а также их интерпретация через свойства сетей Петри. Предложенныйbподход обеспечивает повышение надёжности,bустойчивости и точности измерительных систем за счёт раннего обнаружения и коррекции ошибок на уровне Edge и Fog вычислений.

Ключевые слова: Edge вычисления, Fog вычисления, измерительные системы, обработка данных, сети Петри, верификация алгоритмов, распределённые вычисления, отладка, моделирование.

Abstract: This paper presents an approach to the verification and debugging of measurement data processing algorithms in systems based on Edge and Fog computing architectures. A practical case study demonstrates the behavior of measured parameters under error conditions occurring at different levels of distributed data processing— both at peripheral (Edge) devices and intermediate (Fog) nodes. The impact of latency, partial data loss, and incorrect signal preprocessing on real-time measurement results is analyzed. Methods for error detection and localization using formal mathematical tools, in particular Petri nets, are presented, enabling the modeling of distributed computational processes. The main types of errors arising in decentralized processing environments are examined, along with their interpretation through the properties of Petri nets. The proposed approach improves the reliability, robustness, and accuracy of measurement systems by enabling early detection and correction of errors at the Edge and Fog computing levels.

Keywords: Edge computing, Fog computing, measurement systems, data processing, Petri nets, algorithm verification, distributed computing, debugging, modeling.

Introduction

In the context of developing modern measurement systems based on Edge and Fog computing architectures, formal verification of data processing algorithms becomes particularly important. According to the ISO 9000:2000 standard, verification is defined as confirmation, based on objective evidence, that specified requirements have been fulfilled. In distributed computing environments, this definition is extended to account for the correctness of algorithm operation at different processing levels—from peripheral (Edge) devices to intermediate (Fog) nodes.

Formal verification of software components in such systems represents a set of methods for proving the compliance of data processing models with given specifications. At the same time, debugging of algorithms is considered as a process of identifying, localizing, and eliminating errors that arise in distributed processing environments, where there is no single execution reference and computations occur asynchronously and in real time [5].

Traditional approaches to validating measurement data processing algorithms, based on comparison with reference data, demonstrate limited applicability in Edge and Fog architectures [1]. This is обусловлено высокой динамичностью потоков данных, вариативностью источников измерений и необходимостью оперативной адаптации алгоритмов. A significant limitation is also the dependence on subjective operator evaluation when interpreting results.

From a theoretical perspective, these limitations are associated with insufficient formalization of measurement data processing processes in distributed environments. To ensure proper verification and debugging, it is necessary to represent the system as a formal model that reflects the interaction of components at different levels of the computing infrastructure.

The data processing process in measurement systems involves multiple heterogeneous components that differ in functionality, architecture, and temporal characteristics. In Edge and Fog computing environments, there is a need to transition from the physical level of data representation to abstract models that allow formalization of distributed processing, synchronization, and data transmission.

An analysis of existing approaches to modeling measurement data processing algorithms shows that the use of Petri nets is an effective tool for formal verification [6]. This formalism enables the analysis of properties of distributed computational processes, including parallelism, resource contention, and synchronization, making it particularly relevant for systems implementing Edge and Fog computing.

Methods

To formalize measurement data processing algorithms in distributed Edge and Fog architectures, the Petri net formalism is employed, enabling the representation of parallel and asynchronous computational processes. A Petri net model is defined as a quadruple [5]:

$$C = (P, T, I, O)$$

where $P = \{p_1, p_2, \dots, p_n\}$ is the set of places representing the states of data and computational nodes (sensors, Edge devices, Fog nodes),

$T = \{t_1, t_2, \dots, t_m\}$ is the set of transitions corresponding to operations of data processing, transmission, and aggregation,

$I: T \to P^{\infty}$ — is the input function defining the dependencies of transitions on input states,

$O: T \to P^{\infty}$ is the output function determining the results of transition execution.

In Edge and Fog computing environments, places are interpreted as states of measurement data flows at different levels of the distributed infrastructure, while transitions correspond to preprocessing, filtering, transmission, and data integrationoperations. The condition $P \cap T = \emptyset$ ensures the separation of states and operations within the model..

The system dynamics are described by the marking:

$$\mu: P \to \mathbb{N}$$

which defines the distribution of tokens across the places of the net. Tokens are interpreted as units of measurement information or data packets circulating between Edge and Fog nodes. The vector representation of marking:

$$\mu = (\mu_1, \mu_2, \dots, \mu_n)$$

allows a quantitative description of the system state, including node load and data availability at different processing stages.

A marked Petri net:

$$M = (P, T, I, O, \mu)$$

is used to model distributed measurement data processing, including parallel computations and asynchronous interactions between system components [3]. The structural-functional model of data processing in the Edge–Fog architecture includes stages of data acquisition, local preprocessing at Edge devices, transmission to the Fog level, and subsequent aggregation. For analyzing individual stages, model decomposition is applied, allowing the identification of critical processing segments. As an example, a scenario involving incorrect configuration of processing parameters (e.g., a scaling coefficient) at the Edge device level is considered. This scenario is modeled using a local fragment of a Petri net representing the processes of input, validation, and transmission of initial data. Such decomposition enables analysis of error propagation within the distributed system and assessment of its impact on subsequent processing stages at the Fog level.

Results

To analyze the correctness of measurement data processing in a distributed Edge–Fog architecture, the incidence matrix of the decomposed Petri net is constructed, and the reachability equation is solved to evaluate the possibility of transitioning the system from the initial state to the target state [6]. The incidence matrix of the considered network is defined as:

$$D = \begin{pmatrix} -400 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix}$$

The reachability equation for the analyzed fragment is given by:

$$\mu_f = \mu_0 + X \cdot D$$

where $\mu_0 = (250,1,1,0,0,0)$ is the initial marking representing the initial state of data at the Edge level,

$\mu_f = (0,0,0,0,0,1)$ is the desired final marking,

$X = (x_1, x_2, x_3)$ is the vector of transition firings.

Substituting the initial data yields a system of linear equations:

$$\begin{cases} 400x_1 = 250 \\ x_3 = 1 \\ x_2 = 1 \\ x_1 - x_3 = 0 \\ x_2 - x_3 = 0 \\ x_3 = 1 \end{cases}$$

The resulting system has no consistent solution, indicating that the target state is unreachable under the given initial marking. In terms of the measurement system, this corresponds to the presence of an error in the input data introduced at the Edge processing stage. In this case, the error is associated with an incorrect value of the scaling coefficient supplied to the Edge node before transmitting intermediate results to the Fog level [4].

To eliminate the inconsistency, the initial marking is corrected. After transforming the system into canonical form and applying corrections, the updated system of equations is obtained:

$$\begin{cases} 400x_1 = 400 \\ x_3 = 1 \\ x_2 = 1 \\ x_1 - x_3 = 0 \\ x_2 - x_3 = 0 \\ x_3 = 1 \end{cases}$$

In this case, the solution becomes consistent, and the target state is reachable. From an applied perspective, this corresponds to restoring the correctness of the computational process after correcting the erroneous parameter: the scaling coefficient is adjusted from 250 to 400, ensuring proper processing of the measurement signal within the distributed system.

The second analyzed scenario is associated with the occurrence of looping behavior in the data processing algorithm. For this purpose, a separate decomposed Petri net is constructed, describing the persistent repetition of computational operations without transitioning to the next processing stage. In Edge–Fog architectures, such behavior may result from failure to release buffers after a processing cycle, reuse of outdated values during local filtering, improper completion of predicate checks, or accumulation of intermediate differential values without reset [1].

Such situations pose a significant risk for real-time measurement systems, as they lead to data transmission delays, repeated processing of outdated information, and loss of consistency between Edge and Fog levels. The formal representation of such states using Petri nets enables the identification not only of parameterization errors but also of structural defects in algorithms that affect the stability of distributed computational processes.

Discussion

To identify looping behavior in measurement data processing algorithms implemented in Edge and Fog computing environments, Petri net stability analysis is applied using the incidence matrix and the transition firing vector [6]. Since measurement systems require sequential execution of all data processing operations, the transition firing vector is assumed to be unit:

$$A = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

The stability condition of the net is defined by the requirement that the product of the incidence matrix and the firing vector equals zero:

$$D \cdot A = 0$$

A zero result in this case is interpreted as an indication of cyclic behavior, where the system returns to its initial state without progressing to the next stage of the computational process. For distributed measurement systems, this corresponds to repeated execution of the same operations at the Edge or Fog level without producing a new valid result. The source of looping is identified through analysis of the input incidence matrix. Particular attention is given to places involved in multiple transitions that form closed processing loops. The analysis shows that place p_3 participates in several transitions and forms a cycle, which serves as the source of repeated execution.

From an applied perspective, such behavior may correspond to repeated processing of the same measurement packet, failure to clear intermediate data buffers, repeated execution of filtering procedures without updating input data, or the absence of a proper termination mechanism for local processing loops at the Edge node. At the Fog level, this may lead to repeated aggregation of identical values, accumulation of outdated data, and disruption of temporal consistency in measurements.

Eliminating looping requires correcting the relationships between places and transitions in the Petri net. This can be achieved either manually by modifying the structure of the model or automatically through iterative adjustment of connections until cyclic dependencies are removed. In terms of Edge–Fog architecture, such correction corresponds to redistributing processing logic, modifying data transfer conditions between levels, introducing buffer reset mechanisms, and restricting repeated execution of computational procedures.

The behavior of the measured parameter under looping conditions is characterized by the absence of transition to a new stable state and repetition of identical computational patterns. After correcting the model structure, the parameter begins to evolve according to the algorithm logic and the sequence of distributed processing stages.

The proposed approach enables the formulation of formal requirements for measurement data processing algorithms in Edge and Fog systems and supports the use of Petri nets for analyzing their structural correctness. This provides a foundation for developing automated methods for monitoring, error localization, and improving the reliability of real-time distributed measurement systems [2].

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