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Informational and analytical support of decision-making for ensuring the data safety in distributed systems

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Abstract

An important problem of designing distributed systems is to provide a high level of data safety. To solve this problem, two main methods could be considered. The first method is to place the replicas of data files into computer network nodes. The second method is based on using a redundancy of data files' replicas (copies and prehistory's of replicas) in the network nodes. The paper considers formal models of these two methods that are followed by a brief description of the decision-making process to ensure the preservation of data safety. This process is supported by means of an automated complex consisting of two software modules. These modules solve the problem of the optimal use of the two presented methods, ensuring the data safety in distributed systems. Finally, the application of the proposed approach in the design of logistics and transportation systems is discussed.

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Keywords: Distributed systems; Placement of replicas of data files; Strategies for reserving of data files; Logistics

1. Introduction

Distributed data processing systems based on computer networks are very complex technical systems. A huge number of users communicate with these systems by means of various devices, such as workstations, laptops,

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tablets, smartphones, and smartwatches, etc. The work of distributed systems is based on the interaction of a large number of different software, hardware and information components. At the same time, due to the impact of various negative factors, almost all of these components can fail. Elimination of failures consequences in the distributed data processing system requires a large time and resources consuming. These costs, in turn, lead to downtime in the work of companies. As a result, the companies incur significant losses, direct and indirect. Therefore, one of the most important tasks of designing distributed systems is to ensure high system performance and high reliability of the system.

2. Methods for ensuring data security in distributed systems

A widely used method of increasing the reliability of distributed systems is to ensure a high level of data security. An effective method of increasing the level of data security in distributed systems is the creation and placement in the nodes of the system replicas of data files used by the system [1].

The method of data replication is that a number of identical replicas of data files are placed in the nodes of the network. The replicas placement is done in such a way as to place the replicas as close as possible to the users of the system. This placement of replicas allows to solve several important tasks at the distributed system design stage:

- Reducing the processing time of user requests
- Improving the reliability of the system (if one node with a replica fails, requests are redirected to another able to work node with an identical replica)
- The problem of scaling the distributed system is simplified. For example, with a significant increase in the traffic of requests, additional replicas can be placed in the nodes of the network

To find the optimal location of replicas in the nodes of a computer network, many different methods are used. The class of such problems has a high computational complexity, and a variety of special techniques are used to solve them. Ultimately, all these methods are reduced to an optimization problem in which from all N possible nodes of the network it is necessary to choose M (M <N) nodes that are best for replicas placement in according to some criteria.

Placing replicas on nodes of a computer network increases the reliability of the distributed system. However, in the case of an unreliable computer network, there is a possibility of a failure in the processing of requests in a node with a replica. In this case, the replica can be destroyed for various reasons. To increase the probability of successful processing of requests, it is suggested that in the nodes of the network, in addition to replicas, an additional reserve be placed in the form of several copies and/or prehistory's of replicas.

This additional reserve can be created in accordance with one of the three reservation strategies [2]: strategy I - several replicas with permanent data are used, strategy II - are used prehistory's of replicas with variable data, strategy III - both replicas and prehistory's of replicas are used. In strategy III, when processing a request, copies are first used in accordance with strategy I. If copies are destroyed, then prehistory's are used in accordance with strategy II.

3. The decision-making process on methods of ensuring the data safety

When solving the problem of securing information in a distributed system, it is assumed that the safety of information is primarily ensured by using replicas of data files. It is also assumed that it is possible to use an additional reserve from copies and/or prehistory's of replicas. This additional reserve is used only in situations where the placement of only replicas does not provide specified constraints on the performance of the system. For example, the use of copies and/or prehistory's is advisable in the case when the probability of successful processing of requests in some network nodes is below a specified limit.

The decision-making process of choosing a method for ensuring the necessary level of data safety in a distributed system consists of two stages. These two phases are supported by means of the automated complex. The complex consists of two interconnected software modules which correspond to the two stages of the process. The first module is responsible for finding the optimal placement of replicas of the data files in the nodes of the distributed system.

The work of the first module is described below in this article. The second module is used to calculate the optimal size of the reserve from the copies and/or prehistory's of replicas at the individual nodes of the network.

Fig. 1 shows a process chart of the decision-making process to ensure the required level of data security and the values of other characteristics of the distributed system.

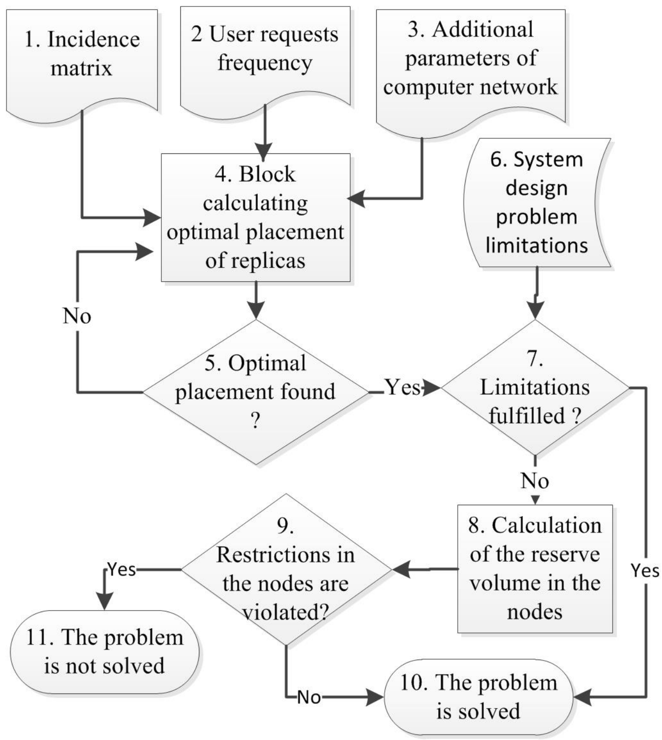

Fig 1. Process chart of the decision-making process.

The program complex uses different input parameters. Below are some of them:

- Network topology and user requests traffic
- The average amount of data transmitted over communication channels when processing requests
- The cost of transmitting a unit of information over communication channels
- The cost of storing replicas and the cost of processing requests in network nodes
- The probability of successful updating/reading of a data file
- Average time to update the replica of the data file
- The average time to create one copy of the data file and average time to repair a replica from its prehistory

In the first phase (blocks 1-5) is solved the problem of determining the optimal placement of replicas on the network nodes. The number of replicas can be fixed or determined when solving a problem.

In the second stage (blocks 6-7), are checked the values of the characteristics of the distributed system functioning in which the replicas are placed. Are checked the values of such characteristics as: the probability of a successful request processing in the network node; the average time of request processing; the cost of storing replicas and processing requests. If the predetermined limit values for system operation characteristics achieved, the problem is solved. If not, search for solutions continues.

For each network node with a replica that has not fulfilled the task limit, calculates the amount of additional reserve to be placed in the node (blocks 7,8,9). Is calculated the number of copies and/or prehistory's, which is necessary to obtain the desired query processing parameter values in each of these network nodes. In [2], the characteristics of the strategies for reserving data files are described, and their effectiveness is compared by various parameters. Also provides formulations and methods for solving problems of optimal choice of reservation strategies. All this allows us to determine the optimal number of copies and/or replica prehistory's to be placed in the individual network nodes.

Below, the article contains the formulation of the problem and a description of the algorithm for solving the problem of optimal placement of replicas in a distributed system. Also, a brief description of the reservation strategies is given.

4. Optimal placement of replicas in a distributed system.

An effective method of increasing the information security in distributed systems is the replicas placement in the nodes of the system. The use of replication methods can also improve the system performance and reliability of its operation. In addition, replication increases the system's ability to scale it. To solve the problem of finding the optimal replicas placement in distributed systems, various methods are used [3-6].

For example, in terms of linear integer programming, the problem of optimal placement of replicas is formulated as follows [3]:

$$\min C = \sum_{i \in F} f_i y_i + \sum_{i \in F} \sum_{j \in D} d_j c_{ij} x_{ij} \tag{1}$$

Subject to:

$$y_i \geq x_{ij}, \quad \forall i \in F, \quad j \in D \tag{2}$$

$$\sum_{i \in F} x_{ij} = 1, \quad \forall j \in D \tag{3}$$

$$y_i \in \{0,1\}, \qquad x_{ij} \in \{0,1\} \tag{4}$$

In expression (1), the first term denotes the cost of deploying replicas over the network nodes. This cost can be defined as the cost of renting servers or renting resources (for example, computing resources or storage devices). The restriction (2) determines that to each end user j there corresponds a node of network i, if there is a replica in this node. Restriction (3) ensures that each user is assigned only one node with a replica. The constraint (4) defines the range of admissible values for the integer variables of the problem y_i and x_{ij}.

Thus, the resulting solutions of this problem is defined by placement of replicas on network nodes and a correspondence between users and nodes with replicas at which the functional (1) has the minimum value with the subject to the limitations (2 - 4).

4.1. An example of the replicas optimal placement problem description

Let us consider a detailed example of the formulation and solution of the replicas optimal placement problem in a distributed system. Suppose that a distributed system is based on a computer network consisting of N nodes. The network topology is represented as an undirected graph $G = (X, T)$. It is necessary to define a subset $\tilde{X}_p$ of p nodes of the set X of network nodes in which it is necessary to place p replicas. This placement of replicas should ensure minimum costs of the operation of the distributed system. The user's information request is sent for processing to the nearest node with a replica. A request for data modification is sent to all nodes with replicas.

We define the following notation:

- $\Lambda_n^e = \|\lambda_n^e\|$ is a vector of dimension *N*, where λ_n^e is the frequency of information requests arising at the node x_n
- $\Lambda_n^u = \|\lambda_n^u\|$ is a vector where λ_n^u is the frequency of the modification requests generated at the node x_n
- d^e, d^u- the average amount of data transferred between nodes of the network when processing the information request and the request for data modification
- $\{v_1, \ldots, v_n, \ldots, v_N\}$ is a vector of "weights" of network nodes, where $v_n$is the average amount of data that node *n* transmits and receives per unit of time when processing requests created at this node: $v_n = (\lambda_n^e d^e + p\lambda_n^u d^u)$
- $dis(x_n, x_j)$ is the length of the shortest path from node x_n to node x_j
- *s* - is the cost of transmitting a unit volume of data along a path of unit length
- $cost\_S(x_n)$ is the cost of storing the replica at node x_n per unit time
- $cost\_E(x_n)$, $cost\_U(x_n)$ are the costs of processing the information request and the data modification request in the nodex_n

The problem of optimal replicas placement in network nodes is formulated as a generalized minisum problem of the p-median. As a criterion of optimality, we will use the minimum costs of the system functioning [7].

For the node x_i, we define the transmission number $\sigma(x_i)$ as the sum of the costs of data exchange between the node x_i and all other nodes of the set *X* when processing requests, which is:

$$\sigma(x_i) = \sum_{n=1}^{N} \left[dis(x_i, x_n) s v_n \right] \tag{5}$$

Let the median of the graph *G* be a node $\bar{x}$ for which the minimum of the transmission number is reached:

$$\sigma(\bar{x}) = \min_{x_i \in X} \sigma(x_i) = \min_{x_i \in X} \left\{ \sum_{n=1}^{N} \left[dis(x_i, x_n) s v_n \right] \right\} \tag{6}$$

Let X_p be the subset of p nodes of the set in which p replicas are placed. We denote by $d(X_p, x_n)$ the minimal distance from a random node x_n of the set X to one of the nodes of the set X_p:

$$\mathrm{d}(\mathrm{X_p}, \mathrm{x_n}) = \min_{\mathrm{x_j} \in \mathrm{X_p}} \mathrm{dis}(\mathrm{x_n}, \mathrm{x_j}) \tag{7}$$

Define the transmission number $\sigma(X_p)$ for the subset X_p, by analogy with formula (8) as follows [7]:

$$\sigma(\mathrm{X_p}) = \sum_{n=1}^{N} \mathrm{v_n} \mathrm{s} \mathrm{d}(\mathrm{X_p}, \mathrm{x_n}) = \sum_{n=1}^{N} \mathrm{v_n} \mathrm{s} \min_{\mathrm{x_j} \in \mathrm{X_p}} \mathrm{dis}(\mathrm{x_n}, \mathrm{x_j}) \tag{8}$$

We call the set $\tilde{X}_p$ as the p-median of the graph *G*, to which the minimum of the transmission number corresponds:

$$\sigma(\tilde{\mathrm{X}}_\mathrm{p}) = \min_{\mathrm{X_p} \subseteq \mathrm{X}} [\sigma(\mathrm{X_p})] \tag{9}$$

We denote by $COST(X_p)$ the cost of functioning of the distributed system per unit of time, in which the replicas are placed among the nodes of the setX_p:

$$\mathrm{COST}\left(X_p\right)=\sum_{j=1/x_j\in X_p}^{p}\mathrm{cost\_S}\left(x_j\right)+\sum_{j=1/x_j\in X_p}^{p}\mathrm{cost\_E}\left(x_j\right)\left(\sum_{n=1/x_n\to x_j}^{N}\lambda_n^e\right)+\sum_{n=1}^{N}\lambda_n^u\left(\sum_{j=1/x_j\in X_p}^{p}\mathrm{cost\_U}\left(x_j\right)\right) \quad (10)$$

In the above formula, the first item is the cost of storage of the replicas, the second item - the information requests processing costs at the nodes with replicas. The third item is the cost of data update requests processing.

Then the problem of the optimal placement of replicas along the nodes of the distributed system will have the following formulation. In an undirected graph $G = (X, \Gamma)$, it is necessary to find a subset $\tilde{X}_p$ of p nodes of the graph that ensuring the minimum of the value of the following functional:

$$F_p\left(\tilde{X}_p\right)=\mathrm{COST}\left(\tilde{X}_p\right)+\sigma\left(\tilde{X}_p\right) \quad (11)$$

Various restrictions can be used in this problem. For example, the restriction on the maximum number of replicas placed on the network nodes: $\left|\tilde{X}_p\right| \leq \bar{P}$. It is possible to use a limit on the amount of information processed by the node having the replica. This volume consists of the amount of data in the queries received by the node per unit of time and the amount of data that the node returns in response to these queries:

$$\sum_{n=1/x_n\to x_i^*}^{N}\left(\lambda_n^e d^e+p\lambda_n^u d^u\right)\leq \bar{D} \quad (12)$$

The formulated problem belongs to the class of problems on finding the p-median of a graph that are NP-hard. For this class of problems, many different methods for their solution have been developed, which make it possible, within an acceptable time, to find a solution close to the optimal solution [8,9].

4.2. An example of an algorithm for solving the problem of replicas optimal placement

Let us consider an example of an algorithm for solving the above problem. The algorithm is a modification of the well-known heuristic method of searching for the p-median of the graph proposed by Teitz M. B., Bart P. in [10]. Description of the algorithm:

- 1-Randomly assigned number p of the graph medians. Then, from the set X of nodes of the graph, p nodes are randomly chosen. These nodes form the set X_p. The nodes of the set X that are not in the set X_p are marked with the label "not tested"
- 2-Randomly, the "not tested" node x_j is selected from the set $\{X \backslash Xp\}$. If there are no such nodes, then go to step 6.
- 3-For each node x_i from the set X_p, the value Δ_{ij} is calculated. It is equal to the value by which the value of the functional F_p changes when replacing the node x_i in the set X_p with the vertex x_j selected at step 2

$$\Delta_{ij}=F_p\left(X_p\right)-F_p\left(X_p{}^i\right) \text{ where } X_p{}^i=\left(X_p\cup\left\{x_j\right\}\right)\backslash\left\{x_i\right\} \quad (13)$$

At this step of the algorithm, it is necessary to remember the index i* of such a node x_i from the set X_p, when replacing it with the node x_j, the maximum value Δ_{ij} is reached, i.e. $\Delta_{i^*j} = \max_{x_i\in X_p}\Delta_{ij}$

- 4-If $\Delta_{i^*j} \leq 0$, then replacing the node of the set X_p by the node x_j does not improve the value of the functional of the problem. Then mark the node x_j as "tested", and go to step 2
- 5-If $\Delta_{i^*j} > 0$, then replacing the node x_{i^*} of the set X_p by the node x_j improves the value of the functional of the problem. We displace the nodes and mark both nodes x_j and x_{i^*} as "tested". As a result, we got a new set

$X_p = (X_p \cup \{x_j\}) \backslash \{x_i\}$, go to step 2

- 6-The end of the algorithm. The resulting set X_p is close to the optimal p-median set $\tilde{X}_p$ of nodes of the distributed system. In these nodes, we need to place replicas of the data file

This algorithm is implemented as a C ++ program module in the MS Visual Studio integrated development environment (IDE). The module is used as part of an automated complex designed to support the decision-making to ensure the data safety in distributed systems.

5. Use of a reserve of replica copies and/or replica prehistory's in the network nodes

To increase the probability of successful requests in network nodes with replicas, it is proposed to place an additional reserve in the form of copies and/or prehistory's of the replicas. An additional reserve is created and used when processing requests in accordance with the three reservation strategies. Below is a description of the process of user requests processing in the nodes of the network.

5.1. Strategy I

Figure 2 shows the behavior of the system when one request is processed to a replica of a data file in the node in which a reserve is created from copies of the replica according to the strategy I is shown in Fig. 2.

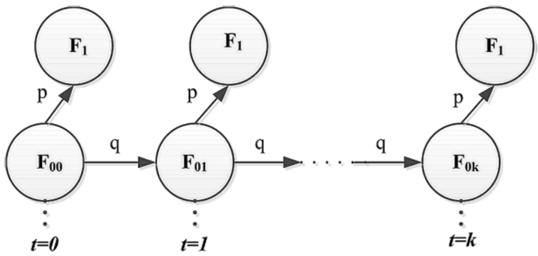

Fig. 2. Strategy I of reservation.

In this case, a replica F_{00} of a file with persistent data and k copies of this replica $(F_{or},\ r = 1,2,\ldots,k)$ are placed in the node of the distributed system. Request processing begins with the use of the replica F_{00}. Let p be the probability that a replica or its copy will not be destroyed in a single time interval when processing the request. Then $q = 1 - p$ is the probability of destruction of the replica or its copy when processing the request for a single time interval. If the replica F_{00} is destroyed, the request processing continues using the copy of the replica F_{01}. It, in turn, can also be destroyed, and the process will continue using the next copy of the replica.

Suppose that a copy of $F_{0r}, r = 0,1,2,\ldots,(k-1)$is destroyed. Then the following $(r-1)$ copy of the replica will be used to complete the request processing, etc.

The probability of successful request processing when using a reserve in accordance with strategy I will be equal to $\rho_I = 1 - q^{k+1}$. The average time to successfully process a request is: $E(T_I^*) = \theta p^{-1}\{1 - q^{k+1}[1 + (k+1)p]\}$.

Here θ is the average time for one attempt to process the request. On the other hand, the average processing time of the request regardless of the processing result is equal to: $E(T_I) = \theta p^{-1}(1 - q^{k+1})$.

5.2. Strategy II

The process of processing a query in a node with a replica and a reserve from the history of this replica is shown in Fig. 3.

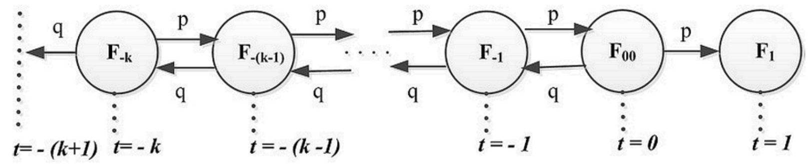

Fig. 3. Strategy II of reservation.

The process of the request processing begins with the use of a replica at the point$(t = 0)$. In this situation, the node contains an unbroken replica of the variable data file F_{00} and the k prehistories of this replica$(F_{-1}, \ldots, F_{-k})$. With probability p the request may be successfully processed. In this case, the process goes to the point$(t = 1)$. If the replica F_{00} is destroyed during the processing of the query with probability q, then the process will go to the point$(t = -1)$. After this, an attempt will be made to restore the replica F_{00} with the help of its prehistoryF_{-1}. As a result, the replica F_{00} can be restored with probability p, and the process returns to the point$(t = 0)$. However, with probability q, the prehistory F_{-1} can be destroyed. Then the process goes to the point $(t = -2)$.

This behavior of the system when processing requests can be considered as a process of "random walk" with two absorbing screens at points $(t = 1)$ and $(t = -(k + 1))$. The probability of successful processing of the request in this case is: $p_{II} = p[p^{k+2} - q^{k+2}]^{-1}[p^{k+1} - q^{k+1}]$.
An average request processing time:

$$E\left(T_{II}\right) = \left[\theta\left(q-p\right)^{-1}\right]\left[k+1-\left(k+2\right)\times\left(1-\left(qp^{-1}\right)^{k+1}\right)\left(1-\left(qp^{-1}\right)^{k+2}\right)^{-1}\right] \tag{14}$$

Strategy III

This strategy is a mixed strategy and uses both copies and prehistories of replicas in accordance with the first two strategies. When processing a request, x copies of the replica are first used in accordance with the strategy I. If all copies are destroyed, then the request processing continues using y prehistories in accordance with the strategy II.

In this case, the probability of successful request processing is: $\rho_{III} = 1 - q^x\{[q^{y+1}(q-p)][q^{y+2} - h^{y+2}]^{-1}\}$.

Average request processing time:

$$E\left(T_{III}\right) = \theta p^{-1}\left(1-q^x\right) + \frac{\theta q^x}{q-p} \times\times \left[\left(y-1\right) - \frac{\left(y+2\right)\left[1-\left(qp^{-1}\right)^{y+1}\right]}{1-\left(qp^{-1}\right)^{y+2}}\right] \tag{15}$$

Formulas for calculating the characteristics of the reservation strategies, presented in this section, were used in the development of one of the software modules of the automated complex (see Section III).

6. Application in logistics and transportation

The proposed approach to ensuring data safety in distributed systems has a wide application potential in the area of logistics and transportation. In particular, it can be efficiently used while solving the following logistics network design tasks:

- Design of logistic information systems
- Supply chain network design
- Transportation network design

Logistic information systems are typically based on computer networks, where a high level of data safety should be provided. Therefore, the proposed approach could be directly applied to the design of logistic information systems. On the other hand, the above-discussed task of optimal placement of p-medians on the nodes of the graph occupies one of the central places among supply chain network design [11]. The p-median problem is that of locating *p* facilities to minimize the demand weighted average distance between demand nodes and the nearest of the selected facilities [9]. Therefore, the proposed method for solving the problem of finding the optimal placement of p-medians can be applied in the field of Supply Chain Management for solving supply chain network design problems, in particular, facility location, capacity location, transportation network design, and market and supply allocation problems [12].

7. Conclusion

The article considers the problem of ensuring the safety of information in distributed systems. To solve it, it is proposed to use two methods together. The first method is to locate replicas of data files on the nodes of the distributed system. Secondly, the use of additional reserve from copies and/or prehistory's of replicas in nodes allows increasing the probability of successful processing of requests in separate nodes of the system. The article gives a brief description of the decision-making process to ensure the preservation of data safety. This process is supported by means of an automated complex consisting of two software modules. These modules solve the problem of the optimum use of the two presented in the article methods. Finally, application of the proposed approach in the design of logistics and transportation systems is discussed. In particular, its application to the following logistics network design tasks is considered: design of logistic information systems, supply chain network design, and transportation network design.

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