Estimation of response time of laser complex
data processing nodes

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Abstract. The work is devoted to problem of information exchange between elements and
devices of a telecommunication network for laser technological complex. The laser complex is
a combination of hardware and software designed to carry out operations based on the use of
laser radiation. Laser complex structure provides a possibility of remote control through a client-
server system built on the basis of TCP/IP protocol. The main requirements for industrial
network of the complex are performance and predictability of information delivery time. To
solve this problem, a probabilistic model for calculating the numerical characteristics of the
distribution of requests timeout for external commands from control/monitoring nodes is
proposed.

1. Introduction

Laser systems are a set of technical (hardware) and software tools intended for carrying out operations
based on using of laser radiation. Laser complexes are indispensable for solving modern problems of
industry [1-4], science [5-7] and medicine [8-10].

To carry out work in the field of materials micromachining with femtosecond laser radiation, an
automated laser complex based on a telecommunication network was developed [11-15]. The complex
is intended to work in the format of remote sessions with the involvement of third-party scientific
groups, providing the possibility of cooperation without territorial reference.

As can be seen from the diagram in figure 1, the most loaded element of a telecommunication
network is a server processing unit, which provides bi-directional data transfer between control devices
and hardware of "technological section". Since the main requirements for an industrial network are
performance and predictability of information delivery time [16,17], it is necessary to evaluate the
response time of the developed system's server to requests from external control/monitoring devices.

2. Probabilistic model for estimating a response time of data processing nodes

To solve this problem, a probabilistic model was built for calculating the numerical characteristics of
waiting time distribution for request execution. The total time of a task execution by the server (i.e., the
maximum response time) is a random variable (RV) \( T \), which, in turn, is the sum of a random number
\( N \) of independent RVs \( X_1, X_2, \ldots, X_N \). Here \( X_i \) is execution time of request with number \( i = 1, \ldots, N \). RV
\( N \) accepts positive integer values.
It is necessary to find the numerical characteristics (expected value $m_t$ and variance $D_t$) of RV $T = \sum_{i=1}^{N} X_i$, if probability density function of RVs $N, X_1, X_2, ..., X_N$ and their parameters are known: $m_n, D_n, m_i, D_i$, and all these SVs are independent and all $X_i$ have the equal probability density function with expected value $m_i = m_x$ and variance $D_i = D_x$.

So, let the probability density function of RV $N$ be given by the equalities: $P\{N = n\} = p_n$ ($n \in \mathbb{N}$), then its expected value is

$$m_n = \sum_{n=1}^{\infty} np_n.$$ 

An expected value of RV $T$ provided that $N = n$, is calculated as the sum of expected values of corresponding number $X_i$:

$$M[T|N = n] = M\left[\sum_{i=1}^{n} X_i\right] = \sum_{i=1}^{n} M[X_i] = \sum_{i=1}^{n} m_x = nm_x.$$ 

Then the total expected value (for all possible $n$), or the first moment of RV $T$ will have the form:

$$\alpha_1[T] = m_t = \sum_{n=1}^{\infty} M[T|N = n] \cdot p_n = \sum_{n=1}^{\infty} nm_x p_n = m_x \sum_{n=1}^{\infty} np_n = m_x m_n.$$ 

To calculate the variance $D_t$, it is necessary to find the second moment of $T$, provided that $N = n$:

$$\alpha_2[T|N = n] = M[T^2|N = n] = M\left[\left(\sum_{i=1}^{n} X_i\right)^2\right] = M\left[\sum_{i=1}^{n} X_i^2\right] = M\left[\left(\sum_{i=1}^{n} X_i\right)\left(\sum_{j=1}^{n} X_j\right)\right].$$

Since RVs $X_i$ are independent, then correlation coefficients between $X_i$ and $X_j$ for $i \neq j$ $K_{ij} = 0$, and correlation coefficients $K_{ii} = D_i = D_x$, therefore:
\[ \alpha_2[T|N = n] = \sum_{i=1}^{n} \sum_{j=1}^{n} (m_i m_j + K_{ij}) = \sum_{i=1}^{n} \sum_{j=1}^{n} m_i m_j + \sum_{i=1}^{n} K_{ii} = \sum_{i=1}^{n} \sum_{j=1}^{n} m_i m_j + \sum_{i=1}^{n} D_i. \]

A total second moment of RV \( T \) (for all possible \( n \)) is equal

\[ \alpha_2[T] = \sum_{n=1}^{\infty} \left( \sum_{i=1}^{n} \sum_{j=1}^{n} m_i m_j + \sum_{i=1}^{n} D_i \right) p_n. \]

Considering \( D_t = \alpha_2[T] - m_t^2 \), \( D_n = \alpha_2[N] - m_n^2 = \sum_{n=1}^{\infty} n^2 p_n - m_n^2 \), the variance \( D_t \) is equal

\[ D_t = \sum_{n=1}^{\infty} \left( \sum_{i=1}^{n} \sum_{j=1}^{n} m_i m_j + \sum_{i=1}^{n} D_i \right) p_n - (m_x m_n)^2 = m_x^2 (\alpha_2[N] - m_n^2 + m_x^2) + D_x m_n - m_x^2 m_n^2 = m_x^2 D_n + D_x m_n. \]

Using these formulas, it is possible to construct the interval \((m_t - \alpha, m_t + \alpha)\), into which RV \( T \) will fall with a given probability \( p_\alpha \). Here it is assumed that \( T \) has normal distribution. According to the central limit theorem [18,19], this assumption is based on facts that RVs \( X_i \) are independent and they have comparable scales. For example, for the value \( \alpha = 3\sigma_t \) (\( \sigma_t \) is the standard deviation of RV \( T \)), the corresponding probability will be equal \( p_\alpha \approx 0.9973 \).

Calculations were carried out for various normal distribution parameters of request execution time \( X_i \) and the number of clients \( N \) (see table 1). We estimated the boundaries of intervals \((m_t - 3\sigma_t, m_t + 3\sigma_t)\) and \((m_t - \sigma_t, m_t + \sigma_t)\), in which a response time falls with a probability of 0.9973 and 0.6826, respectively. In other words, 99.7% and 68.2% of requests will be executed in these time intervals.

**Table 1.** Experiment parameters for calculating request execution time.

| Experiment number | 1   | 2   | 3   | 4   | 5   |
|-------------------|-----|-----|-----|-----|-----|
| Minimum number of clients | 1   | 2   | 3   | 4   | 5   |
| Maximum number of clients | 3   | 4   | 5   | 6   | 7   |
| Average number of clients \( m_x \) | 2   | 3   | 4   | 5   | 6   |
| Average request processing time \( m_n \), sec | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Variance of number of clients \( D_x \) | 0.111 | 0.111 | 0.111 | 0.111 | 0.111 |
| Variance of request processing time \( D_n \) | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |

In addition to standard deviation, the absolute value of the deviation was also calculated – the variation coefficient \( c_t = (\sigma_t/m_t) \cdot 100\% \). It allows to compare a standard deviation of values with different expected values. The calculation results are shown in table 2.

**Table 2.** Distribution characteristics of request execution time.

| Experiment number | 1   | 2   | 3   | 4   | 5   |
|-------------------|-----|-----|-----|-----|-----|
| Average response time \( m_t \), sec | 0.6 | 0.9 | 1.2 | 1.5 | 1.8 |
| Variance \( D_t \) | 0.12 | 1.13 | 0.014 | 0.016 | 0.017 |
Thus, the calculation results allow us to draw the following conclusions:

- an average response time is directly proportional to the number of clients and varies from 0.6 sec to 1.8 sec with a total number of clients from 3 to 7;
- with an increase in standard deviation, a decrease in variation coefficient of is observed, i.e. variance of the obtained values in relative terms, the less the more clients connect to the server;
- the telecommunication network provides a system operability with an average response time 0.6 sec with a typical case of simultaneous connection of 3 control / monitoring devices to the server, which fully meets both needs of industrial production and experimental research.

3. Conclusion
Thus, the calculation results allow us to draw the following conclusions:

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