HIGH PERFORMANCE PROCESSING CLUSTER FOR REMOTE SENSING SPACECRAFTS

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Abstract. Recently, there has been a tendency to complicate real time control algorithms, to process a large amount of information from the satellite payload (optical, radar, communication systems) directly on board and to create highly informative communication lines with both ground stations and other satellites. The conditions of outer space (vacuum, radiation) impose significant restrictions on the computing capabilities of onboard equipment, which is used as an onboard digital computer complex, and lead to a significant increasing in the cost of space components. A high-performance and relatively cheap computing cluster structure of an on-board computer based on widely available single-board minicomputers is proposed, which allows distributing the computing load among several nodes and simultaneously backing up the system. As a component of a computing cluster, it is proposed to use a computing cluster system based on COTS (Commercial off-the-shelf) components, which increases performance by several orders while reducing cost. Calculations have shown that the introduction of redundancy and distribution of computational tasks makes it possible to achieve an MTBF of about 3 years, which is quite enough for the active existence of university satellites. The proposed structure of the onboard computer complex is installed on the university satellite for remote sensing of the Earth in the visible range with controlled optical magnification, after the launch of which it is planned to confirm the reliability of the results obtained in this work. An assessment of the performance and reliability of such a cluster system is given, which has shown the possibility of implementing such a system on a university satellite for Earth remote sensing.

Keywords: COMMERCIAL OFF-THE-SHELF COMPONENTS, COMPUTING CLUSTER, EARTH OBSERVING SYSTEM, ON-BARD COMPUTER, RASPBERRY PI 3 MODEL B.
Introduction

Spacecraft have recently been subjected to stringent performance and on-board information volume requirements, primarily related to the complexity of real-time control algorithms and the processing of large amounts of data generated by the payload (optical, radar and communication systems) and sensors.

To solve such problems, there are OBCs (Onboard Computer) specially designed for space environment, the cost of which can exceed $ 20,000, while their computing power is rather low, 50 MIPS (million instructions per second) [1].

The project DM7 (Dependable Multiprocessor) [2] sponsored by NASA (National aeronautics and space administration), Honeywell and CASIS (Center for the advancement of science in space) included development of a multiprocessor cluster of COTS (Commercial off-the-shelf) components [3]. Such a cluster was installed on the ISS in 2016 and was located on the external stand of the NREP station (NanoRacks External Platform). The OBC was based on the Variscite
processors. The cost of one Variscite module starts from $24, it is available for sale, and performance can vary from 900 MIPS [4].

The results of the experiment showed that cluster system built on COTS components can achieve high performance at a much lower price and provide a huge degree of computational reserve and resistance to space factors.

**Formulation of the research problem**

The purpose of the research is to synthesize the structure of a computing cluster with high performance and relatively low cost based on widely available single-board minicomputers, as well as to assess its computing capabilities and reliability.

The installation of the cluster is planned on a university satellite being developed at the Dnepr National University.

At the fig. 1 was shown a general view of a satellite with dimensions of 200x200x400 mm. The main purpose of the satellite is imagining the Earth’s surface with controlled optical and digital zoom, as well as the ability to process information on board, which required significant computing power.

**Figure 1 – General satellite view**

A Canon PowerShot SX40 digital camera is used as a payload. The main characteristics of the digital camera and images of the Earth's surface are given at tab. 1 and tab. 2.

**Solution of the problem**

To solve this problem, we propose a cluster system of four Raspberry Pi 3 Model B minicomputers, the performance of which is 2458 MIPS each [5]-[7], three to be used as computing nodes and one more, for arbitration purposes (fig. 2). Each minicomputer (Rpi00, ..., Rpi03) has its own drive (SD_card_00, ..., SD_card_03) with the Linux operating system, as well as a drive (Shared_mem_00, ..., Shared_mem_03) for setting up a shared resource between computing modules. Minicomputers are connected via Ethernet using a switch with a data transfer rate of up to 100 Mbps. Such a configuration will improve the performance of computing processes, as well as achieve three-fold redundancy of computing power.

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Changing focal distance, mm</td>
</tr>
<tr>
<td>Optical zoom</td>
</tr>
<tr>
<td>Digital zoom</td>
</tr>
<tr>
<td>Number of effective pixels, MPixels</td>
</tr>
<tr>
<td>Maximum image size, pixels</td>
</tr>
<tr>
<td>CPU</td>
</tr>
<tr>
<td>Maximum aperture</td>
</tr>
<tr>
<td>Focusing system</td>
</tr>
<tr>
<td>File format</td>
</tr>
<tr>
<td>Dimensions, mm</td>
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<tr>
<td>Mass, g</td>
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</tbody>
</table>

<table>
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<tr>
<th>Table 2</th>
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<tbody>
<tr>
<td>Orbit height, km</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>400</td>
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<tr>
<td>600</td>
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<tr>
<td>600</td>
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<tr>
<td>800</td>
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<td>800</td>
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</tbody>
</table>

The set of tasks to assess performance will include such resource-intensive operations as Kalman’s filtration to improve the accuracy of measurements of space sensors and the
compression of information (from the satellite's optical and radar systems) by various methods at the same time.

Cluster work (fig. 2) is based on the distribution of tasks among computing nodes (Rpi00, ..., Rpi03). At any given time, one node acts as an arbiter, the other three as computing devices [8]. There is a hierarchy of nodes inclusion, which enables achieving redundancy of computing power.

![Cluster structure based on Raspberry Pi 3 Model B](image)

Figure 2 – Cluster structure based on Raspberry Pi 3 Model B

During the first start of the system, the Rpi00 computing node becomes the arbiter. This node will perform an administrative role and provide access to Shared_mem_00 memory to other three (Rpi01-Rpi03) as long as its functions are performed correctly. When an event occurs that shows the failure of the arbiter, the administration functions will go to the next node in the hierarchy, that is, Rpi01, and Shared_mem_01 will become the shared memory for performing calculations.

Data collecting from sensors, as well as running orientation and stabilization algorithms are performed by computing nodes. Each node has access to the sensor data bus.

The approximate cluster performance is 3.463 GFlops [9]. Using more than one computing node, in parallel computing, reduces its overall efficiency due to the low-speed network connection of 100 MB/s (fig. 3), where the degree of acceleration is determined by the ratio of the time spent on parallel processes of the cluster to the execution time of the computing process by one node. The problem is solved [10] by using the latest version of the Raspberry Pi 4 equipped with a 1 Gigabit network card.

![Cluster and single board performance comparison](image)

Figure 3 – Cluster and single board performance comparison

To assess the reliability of the cluster system, a computational model was constructed according to the node connection scheme (fig. 4). There are failure rates of a distributed memory (solid state drive), a memory card for the Raspberry Pi, the Raspberry Pi 3 Model B processor – BCM2837 and a network switch, respectively (tab. 3).

Due to the fact that the failure rate of the BCM2837 Raspberry Pi 3 Model B processor is not defined in the technical documentation, we calculate its value from the element base shown at fig. 5.

The failure rate of the Raspberry Pi 3 Model B was found according to the method described in [11] and CPU principal scheme shown at fig. 5. The calculation is determined by the expressions:
The failure rate of capacitor is:

\[ \dot{\lambda}_C = \dot{\lambda}_B K_C K_S K_{SR} K_E K_Q, \]  

where

- \( \dot{\lambda}_C \) – failure rate of the capacitor;
- \( \dot{\lambda}_B \) – basic capacitor failure rate;
- \( K_t \) – coefficient of temperature regime accounting;
- \( K_C \) – coefficient taking into account the value of the nominal capacitance of the capacitor;
- \( K_S \) – coefficient taking into account the value of the electric load of the capacitor;
- \( K_{SR} \) – coefficient taking into account the effect of series resistance;
- \( K_E \) – coefficient of influence of the rigidity of the operating conditions of capacitors and microprocessors;
- \( K_Q \) – quality factor of manufacturing capacitors and microprocessors.

The failure rate of BCM2837 processor is:

\[ \dot{\lambda}_{BCM2837} = (\dot{\lambda}_c K_C K_{Fp} + \dot{\lambda}_B K_{Fp}) K_A K_Q + \dot{\lambda}_{deb}, \]
where
\( \lambda_{BCM2837} \) – failure rate of the BCM2837 processor;
\( \lambda_{cr} \) – failure rate of the microprocessor due to the crystal;
\( K_{cr} \) – coefficient taking into account the number of transistors on a chip;
\( \lambda_{ch} \) – microprocessor failure rate associated with the type of housing;
\( K_{ch} \) – coefficient of the type of housing;
\( \lambda_{Pr} \) – coefficient taking into account the manufacturing process of the microprocessor;
\( \lambda_{dis} \) – failure rate due to electrostatic discharges sensitivity.

Failure rate of the processor assembly is:

\[ \lambda_3 = (\lambda_{BCM2837} + \lambda_{cr} + \lambda_{CLC} + N\lambda_{cir}), \tag{3} \]

where
\( \lambda_3 \) – failure rate of the processor assembly BCM2837;
\( \lambda_{CLC} \) – resonator failure rate;
\( \lambda_{cir} \) – failure rate due to soldering;
\( N \) – Number of soldering places (estimated number – 1500);

Failure rate of cluster system is:

\[ \lambda = \left( \frac{\lambda_1 + \lambda_2 + \lambda_3}{m} \right) + \lambda_4, \tag{4} \]

where
\( \lambda \) – system failure rate;
\( m \) – redundancy degree;

MTBF of cluster system is:

\[ T_5 = \frac{1}{\lambda} \tag{5} \]

### Table 3

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure rate ( \lambda ), (10^{-6}) hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raspberry Pi 3 Model B</td>
<td>82.9</td>
</tr>
<tr>
<td>SD card Innodisk [12]</td>
<td>0.33</td>
</tr>
<tr>
<td>SSD Innodisk [13]</td>
<td>0.33</td>
</tr>
<tr>
<td>Switch D-Link [14]</td>
<td>2</td>
</tr>
</tbody>
</table>

Thus, the MTBF of the proposed cluster system (fig. 6) with 3-fold redundancy is about 24,000 hours, or about 3 years.

**Scientific novelty**

The structure of a cluster system based on single-board computers such as Raspberry Pi 3 Model B has been synthesized for university satellites for the first time in Ukraine. It distributes the computational load between several nodes, allows achieving a total performance of about 3 GFlops and reduces component costs by almost two orders of magnitude compared to the specialized space production.

**Conclusion**

Calculations have shown that the introduction of redundancy and distribution of computational tasks makes it possible to achieve an MTBF of about 3 years, which is quite enough for the active existence of university satellites.

The proposed structure of the onboard computer complex is installed on the university satellite for remote sensing of the earth, after the launch of which it is planned to confirm the reliability of the results obtained in this work.

**References**


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