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SUPERCOMPUTERS: CURRENT STATUS AND DEVELOPMENT PROSPECTS

The article analyzes the current status of supercomputer technologies and their distribution dynamics on different indicators. The development dynamics of supercomputers in recent years is studied.

Keywords: *supercomputer, real productivity, theoretical productivity, green computing, big data, flops, cluster, computing systems, microprocessor*.

Introduction

The establishment of information society in Azerbaijan has been accepted as one of the main priorities of the government policy. The main duties of establishing the information society include the development of legal fundamentals of this society, strengthening economic, social and intellectual potential of the country, formation of modern information-communication infrastructure, provision of information security, integration into global information space and other important issues. Supercomputers with high computing productivity and large memory are widely used to rapidly process the data that require complex computations and large volumes of data and occur during solution of indicated problems and deliver them to the users. At the same time, computing power of personal computers does suffice for solution of complex problems that require large computing and memory resources and occur in different fields of science: physical-chemical processes, nuclear reactions, modeling of global atmosphere processes in real time period, cryptography, geology, creation of new drug types etc. [1]. For this reason, supercomputers are widely used to solve such complex problems.

Parallel computing systems and architecture of supercomputers

Supercomputer is a computing system that exceeds in manifold the technical indicators (operating memory size, storage size of external disk enclosures, price, energy expenditure etc.) and computing power of existing computers. Supercomputer term was used, for the first time, by George Michael and Sydney Fairbank, employees of Livermore National Laboratory named after E.Lawrence in 1960s (California, USA). Supercomputers are developed on the basis of the parallel computing systems. Classification of parallel computing systems was proposed by American scientist G.Flynn for the first time in 1964 [1, 2]. Based on this classification, architecture of computing systems is created on the basis of the instructions flow and mutual relations of data flow. As known, instructions and data are processed consecutively in classic architecture of computing devices. Instructions and corresponding data are called to arithmetic -logic unit and implemented consecutively. But, function principles differ for computing systems. Classification proposed by G.Flynn is as following:

- *SISD-Single Instruction, Single Data*;
- *SIMD-Single Instruction, Multiple Data*;
- *MISD-Multiple Instruction, Single Data*;
- *MIMD - Multiple Instructions, Multiple Data*.

SISD architecture matches the architecture of classic computing devices (proposed by Fon-Neimann). Such systems consist of one central processor; instructions are consecutively implemented on data. In such type of computing systems instructions and data (operands) written for solution of any problem are extracted from the memory one by one, implemented, and results are recorded into the memory in the end.

In the second type of computing systems, operations are run on multiple data. There are tens of thousands of processes in such systems. Same operations can be run on different data using one instruction. Vector and matrix systems can be sited as examples for such systems. In these systems, it is possible to conduct the same operation on all elements of a vector or matrix using one instruction. One processor element is used for each element.

Multiple instructions' flow is executed on one data in the third type of computing systems. Supercomputers operating on this principle are not used in practice for time being.

Architectures operating on MIMD principle are mainly used in parallel computing systems. Such systems provide parallel implementation of several instruction flows on different data. Computing systems with multiple architectures operating on MIMD principal – supercomputers were developed. Three types of architectures, based on MIMD principle, are widely used in the development of Supercomputers: SMP, MPP and cluster [3]. SMP (*Symmetric multiprocessing*) – general physical memory is used to provide the connection between the processors in computing system with symmetric multiprocessor archicture. Processors mutually connect with each other through general memory. Each of processors has an equal right while requesting any address from the memory. For this reason, systems with SMP architecture are called symmetric systems. SMP – systems are developed based on high-speed system buses (*SGI Power Path, Sun Gigaplane, Dec Turbolaset* etc). This system has following advantages:

- use of general memory allows for rapid exchange of information among processors:
- simple and universal for programming;
- users are capable of using the memory in any volume;
- there are multiple tools for automatic effective parallelization of problems;
- simple exploitation. regular air conditioners working in room conditions are used in such systems;
- not very expensive.

Disadvantage of the SMP system is poor scaling of general memory systems.

Indicated disadvantage does not allow wide use of these systems. The reason for difficulty of the wide scale use is the application of the general bus. This bus allows information exchange between two devices at the same time period. For this reason, request of several processors to the same part of the memory causes conflict situations and computing joints interfere with each other's operation. Occurrence of such conflicts heavily depends on common bus speed and number of processors participating in the system. There are no more than 32 processors in systems with SMP architecture. Such systems are mainly used for creation of work stations and servers.

MPP - Computing systems with *Massively Parallel Processors* are more widely spread in comparison with SMP architecture. In such systems, memory is physically distributed among processors. MPP system is developed out of processors and separate modules with memory using a commuter. In such systems, each model behaves like a fully functional computer. Only processors connection to each memory model can address them. In this architecture operating system can work in two options. In the 1st option, one of these modules is selected as the controlling computer (front-end) and operating system fully loaded onto it, simplified version of the operating system is loaded on other modules. In the 2nd option, operating system in fully loaded on each module. Computing system with MPP architecture can be scaled well. Synchronization of processors performance in such systems is easy. Supercomputers created on the basis of this architecture have high computing productivity. These systems combine tens of thousands of processors. ASCI *Red* and ASCI *Blue Pacific* supercomputers can be sites as examples for these. These systems have several disadvantages:

- as general memory is not used, inter-processor information exchange speed is low;
- each processor uses a small, local memory in its possession;
- Special software providing inter-processor information exchange is used.

Supercomputers with MPP architecture use *MPI, PVM, BSPlib, Corba* and other application packages in order to divide complex problem into sub-problems and distribute them among computing joints. *NUMA* (*nonuniform memory access*) hybrid architecture is used for the development of some supercomputers. This architecture combines SMP and MPP architectures. In NUMA, the computing system is created by combining SMP modules with local memory using high-speed communication network through general physical memory.

Recently, supercomputers are developed on the cluster architecture. In the 46th rating table of 2015, 85.2% of supercomputers, produced in the world, , have the cluster architecture.

Cluster – is a computing system that combines more computers (computing joints) using network technology (through common bus commuters etc.). Server, workstation, personal computer or blade-servers can be used as computing servers. If one the computing joint is out of order, then other computing joints overtake its operation, which is the advantage of the cluster system in comparison with other systems. Cluster system consists of separate modules. Each module is assembled of existing standard off the shelf assembly elements - processors, commuters, operating memory and disk memory device. The price of computers, based on this architecture, is very cheap. These supercomputers are assembled on existing compiling elements (off the shelf) – processors, commuters, operating memory, disk memory and external devices. Network technology (Fast/Gigabit Ethernet, Myrinet etc.) are used for connecting indicated modules. Cluster type computers are very simply to assemble, repair and control. Cluster systems are cheap, easy to install and operate. For this reason, this architecture is widely used to develop supercomputers worldwide. *Linux*, *Unix*, *MS Windows* and other operating systems are widely used for supercomputers. *PVM*, *MPI*, *OpenMP* and other application programs are widely applied in supercomputers for solution of complex problems [1, 4].

PVM (parallel virtual machine) was developed in 1991. Provides parallel implementation of a program divided into subprograms in multiprocessor computing systems (with cluster architecture) consisting of different types of computers (processors).

MPI (Message passing interface) was developed in 1993. Provides parallel implementation of a program divided into subprograms in multicore and multiprocessor computing systems with distributed memory (with MPP architecture). Exchange among computing joints is carried out through exchange commuters (*Gigabit Ethernet*, *Infoband* etc.).

Open MP (*Open Multi Processing*) was developed in 1997. Provides parallel implementation of a program divided into subprograms in multicore and multiprocessor computing systems with general memory (with SPM architecture).

Supercomputers are used for solution of complex problems occurring in different fields of science indicated below [5]:

- theoretical and experimental physics, high energy physics, quantum physics etc.;
- quantum and molecular chemistry;
- mathematical modelling of large systems;
- chemical engineering, computational chemistry, creation of new materials;
- engineering industry;
- ecology;
- genetics;
- modelling of processing occurring on earth, ocean and atmosphere;
- astronomy;
- military, etc.

Determination of computing productivity of supercomputers

One of the main indicators of multiprocessor computing systems is their computational productivity. While compiling supercomputers' rating table, their computing productivity is considered as the main indicator. The number of operations, executed in a second, is the computing productivity of the supercomputer. Productivity of supercomputers is evaluated through theoretical and real productivity. To calculate the theoretical productivity, we must multiply the productivity of one of the same type processors participating in the system by the number of processors. Real productivity is determined using special testing programs [6]. Real productivity comprises approximately 70-90% of theoretical productivity. In order to determine the productivity of supercomputers, Flop/s - floating point operations per second is used.

Calculation of the theoretical productivity of supercomputers comprised of blade servers (microprocessor) is as following:

Assumingly,, the supercomputer was assembled on two microprocessor *Intel E5-2650 blade* servers. Each microprocessor consists of eight cores operating on pipelining principle (consisting of eight blocks). Each microprocessor executes 8 operations during one stroke. If operational speed of the processor is 2 Ghz, then theoretical productivity of one core can be calculated as following:

8 Flop/stroke * 2 Ghz (stroke/second) = 16 GFlop/second.

Full execution of any machine instruction in the microprocessor core is implemented within one stroke. Execution of one instruction approximately passes through the following stages: loading of instructions and data, decoding instruction, execution of instruction and finally, recording of the result. The afore-noted process is for the simplified condition of instruction implementation. In reality, more microprocessor strokes are used for operation implementation. Considering that microprocessors work according to pipelining principle, next instruction is provided at each stroke to the entrance of microprocessor. Each instruction processed in the microprocessor is passed on to the next stage after each stroke. Finally, the result of processed instruction is obtained at the exit of the pipeline.

Thus, it is possible to execute several instructions in parallel during the float of one stroke at the same time. Processor implements not one, but eight instructions during one stroke. Productivity of the noted blade server is calculated as following:

16 GFlop/s/core * 8 core/CPU * 2 CPU = 256 GFlop/s.

In order to obtain the noted productivity in blade servers, it is necessary to divide the solved problem (program) into 16 problems (programs) and direct each of them to the core. Let’s assume that any supercomputer is assembled of 4000 units of noted blade servers. Then, we can determine theoretical productivity of the supercomputer by multiplying the productivity of one blade server by their number. In the indicated case, theoretical productivity of the supercomputer is determined as following:

4000 * 256 GFlop/s = 1024000 GFlop/s =1024 TFlop/s= 1, 024 PFlop/s.

Testing software is used in order to determine the real productivity of a supercomputer. LINPACK is the most popular testing software [1, 4]. LINPACK testing software was developed by J.Dongarra, employee of Argonne National laboratory operated by the University of Chicago,USA in 1979. This is testing software written to solve linear algebra formulas with NxN (1000x1000) unknown. These testing softwares are widely used to develop worldwide supercomputer rating tables.

Analysis of current status of supercomputer technologies

The first supercomputer (CRAY-1) was developed by an American scientist Seymour Cray in 1976. That supercomputer executed 160 million operations per second, its operating memory equaled to 8 megabytes and priced at 8.8 million US Dollars [4]. As of 1993, computer experts of Lawrence Berkeley National Laboratory in the US annually publish the rating table of the most powerful 500 supercomputers in the world (in recent years biannually – in June and November). In November 2015, the 46th rating table of supercomputers published, which is shown in Table 1 [7].

Table 1.
Supercomputers rating table

Order N	Name of organization and country	Computer names and manufacturers	Number of cores	Real productivity (TFlop/s)
1	*National Super Computer Center* (Guangzhou, China)	*Tianhe-2 (MilkyWay-2)* (University of National Defence Technologies)	3 120 000	33 862.7
2	*Oak Ridge National Laboratory* (Oak Ridge, USA)	*Titan (Cray Inc.)*	560 640	17 590
3	*Department of Energy's National Laboratory* (California, USA)	*Sequoia (IBM)*	1 572 864	17 173.2
…	…	…	…	…
100	*HLNR Hannover University* (Germany)	*Gottfried (CRAY XC40)*	40 320	829.8
...	...	…	...	...
300	*CSIR Fourth Paradigm Institute* (India)	*Cluster Platform 3000 (HP)*	17 408	334.4
...	...	…	…	…
500	*University Regensburg* (Germany)	*QPACE2 (Eurotech)*	15 872	206.4

As you can see, *Tihanhe-2* (Milky Way-2) supercomputer located at National Super Computer Center in Guangzhou city of China ranks first. *Tianhe-2* consists of 3,120,000 cores, and has 2 33,800 TFlop/s (10^{12} Flop/s) computing productivity, its price equals to 290 million US Dollars.

Comparison of supercomputers rating table for ten years demonstrates that the supercomputer ranking first in 2005 had only 136 TFlop/s computing power and the computer ranking 500th had 1.2 TFlop/s productivity. Productivity of the computer ranking first in 2015 exceeds the productivity of the supercomputer of the same rank in 250 times. It must be noted that productivity of the supercomputer ranking first ten years ago is 164 Tflop/S less than the productivity of the supercomputer ranking 500th in current table. This is an indicator of the rapid increase of productivity of the supercomputers.

The supercomputer ranking 5th has not changed in the past two years. This demonstrates that the rational use of supercomputers, rather than their computing power, is brought into the forefront. Currently, the productivity of 82 supercomputers is higher than 1 Pflop/s.

Analysis of distribution of supercomputers among countries demonstrates that 39.8% of supercomputers ranking in the rating table belong to USA (Figure 1).

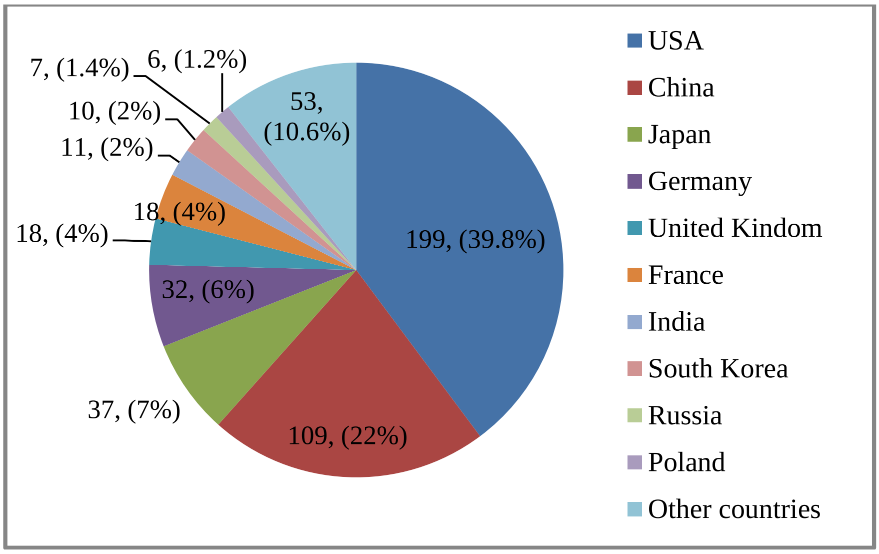


Figure 1. Distribution of supercomputers among countries.

Broad changes have taken place in the architecture of supercomputers manufactured during the recent years. Formerly manufactured supercomputers were made on the basis of *MPP* and *SMP* architectures. Currently manufactured supercomputers increasingly have cluster type architecture (Figure 2). Supercomputers with cluster architecture were created on the module principle; this allowed using them more efficiently. Supercomputers with cluster architecture are less costly than supercomputers with other architectures, which has stimulated their mass production.

Conducted researches demonstrate that majority of supercomputers (46%) are used in an industrial field. At the same time, 25% are used in scientific research, 21.8% in education works, 6% in government projects, and 1.2% in manufacturing facilities (Figure 3).

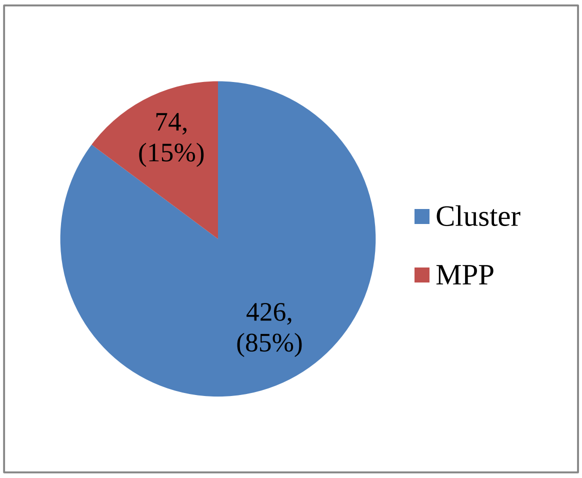


Figure 2. Distribution of supercomputers by architecture

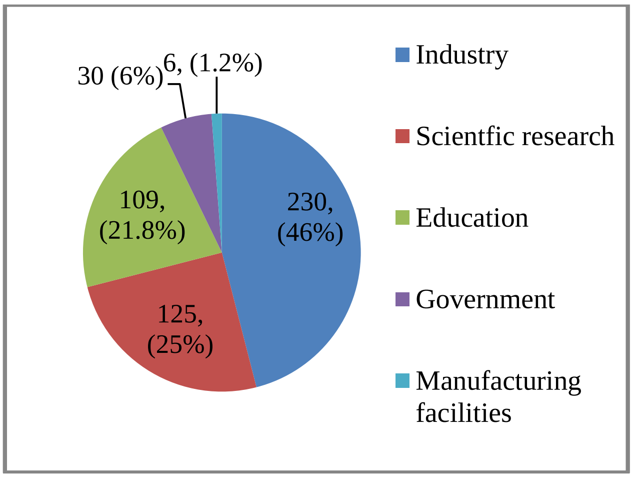
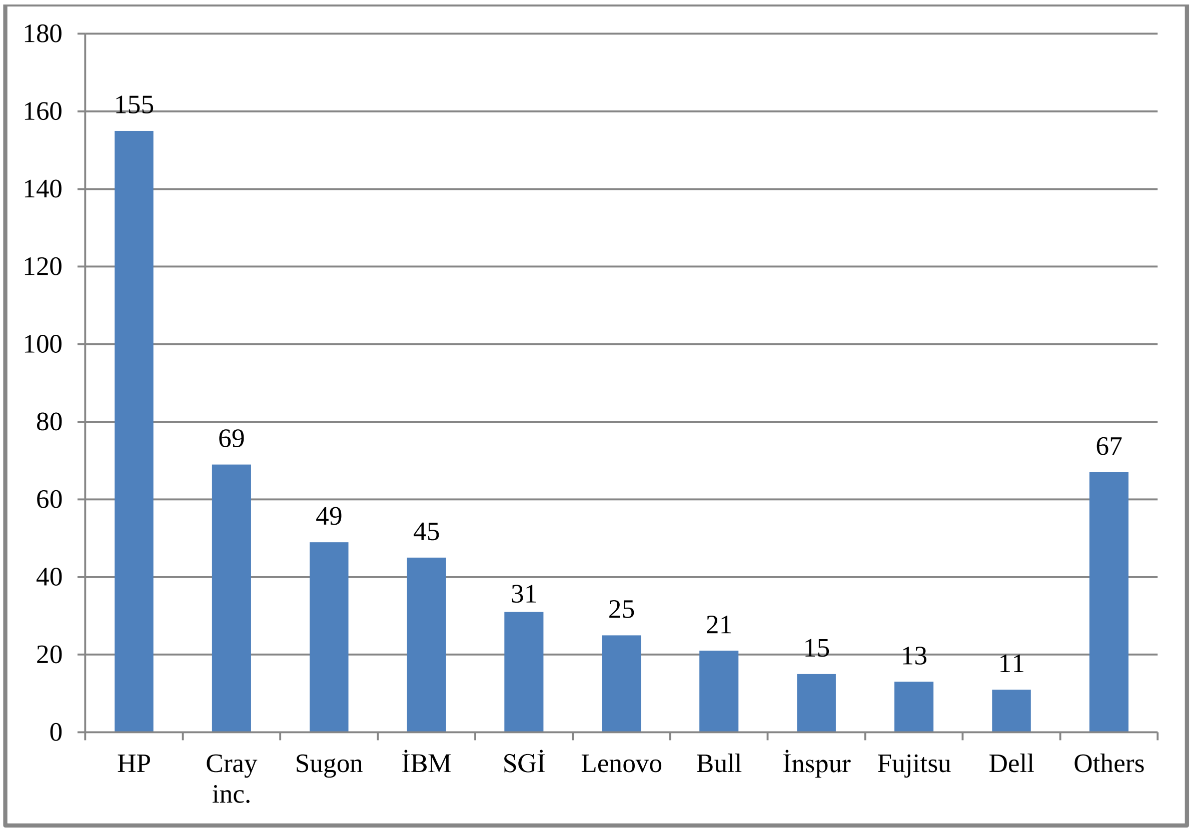


Figure 3. Distribution of supercomputers by the field of use

Out of 500 computers shown in the rating table, 155 were assembled using HP equipment, 69 using Cray Inc. and 49 using Sugon equipment. Supercomputers assembled based on *IBM* (45), *SGI* (31), *Lenovo* (25) and *Bull* (21) companies' equipment rank in lower positions. *Tianhe*-2 supercomputer that ranks first was assembled by *NUDT* (National University of Defense Technology). Distribution of supercomputers by manufacturing companies is shown in (Figure 4)



Picture 4. Distribution of supercomputers by manufacturing companies

Linux based operating systems are used by 487 supercomputers out of 500, and. 212 out these supercomputers are in the Western hemisphere (North America – 205, South America – 7). In Asian countries, there are 174 supercomputers. Europe ranks third with 108 computers. Australia has 6 supercomputers in its possession.

Communication network providing connection among computing joints of supercomputers are installed on the basis of *Infiniband in* 47.4% (237), *10G* in 23.8% (119), *Individual* in 14.8% (74), and *Gigabit Ethernet* in 12.4% (62). 432 out of 500 supercomputers were assembled based on Intel (86.4%), 26 based on (5.2%) *Power*, 21 based on (4.2%) *AMD* and 5 based on (1%) *Spark* microprocessors.

Development perspectives of Supercomputers

Currently, supercomputer technologies are widely used to process and record Big Data and solve complex problems that require great computing and memory [8]. Based on the researches, conducted by IBM company's experts, 15Pbite of data is produced every day (scientific articles, pictures, audio-video files, social network report etc). *Tianhe-2* (China) supercomputer with high productivity has 40 Pbyte memory storage, while *Titan* (USA) has 40 Pbyte memory storage. The memory storage of supercomputer located in Utah National Security Agency (Utah, NASA – USA) equals to 1 Ybyte (yottabyte) - 10^{24}. Noted memory storages are overly large. For the comparison, it needs to be noted that all books written to date can be fit into 400 Tbyte memory. Development in different fields of science will increase the volume of data to be processed exponentially. In the future, this will lead to use of supercomputers with high computing productivity and memory storage. The computing power of supercomputers used for simulation of the mathematical model created for determination of atmospheric processes equals to 4 Tplops (during 4 hour computational period). Supercomputer with computing power of 1 PFlop is required to research structural characteristics and stability factors of DNA.

Development dynamics of the supercomputer, to be manufactured in 2020 (To rank 1st in Top 500), is forecasted as following (Table 2) [9].

Table 2

Development dynamics of supercomputer productivity

Years	Real productivity (PFlop/s)	Theoretical productivity (PFlop/s)
15.11.2015	84.7	137.1
15.11.2016	158.6	256.7
15.11.2017	296.8	480.6
15.11.2018	555.6	899.6
15.11.2019	1.040	1.684
15.11.2020	1.947	3.152

Currently, works are carried out in *Oak Ridge National Laboratory*, Japan, location of *Titan* supercomputer ranking 2nd in the rating table, to develop a new supercomputer titled *Summit* with planned commissioning in 2017. The power of the newly developed supercomputer is planned to exceed by 5 times and equal 150 PFlop/s [7].

Works are conducted towards the development of a new *Aurora* supercomputer based on *Mira* supercomputer with 10 PFlop/s computing productivity, ranking 5th in the rating table and located at Argonna National Laboratory, USA. The computing power of the new supercomputer will be 180 PFlop/s, and will be put into operation in 2019.

Energy consumption of supercomputers is overly great. For example: Energy demand of *Tianhe-2* is 17.8 MW, energy demand of *Mira* is 8.6 MW etc. Annual energy expense of *Tianhe-2* supercomputer is 24 million dollars. *Green Computing* technologies are widely used in order to eliminate the noted problem [10, 11]. Green computing is ecologically oriented information-telecommunication technology. Computer products created upon this technology must meet requirements, such as low use of dangerous materials, low power consumption, long term exploitation period of equipment, cost effective utilization without environmental damage etc. With the help of this technology, next generation *Summit* supercomputer developed on the basis of *Titan* supercomputer, located at *Oak Ridge National Laboratory,* will have 5 times more theoretical productivity by consuming 1.21 times more power. The same is applicable to *Mira* located at *Argonne National Laboratory United States,* and next generation *Aurora*. Thus, when theoretical productivity of *Mira* is 3 945.00 kW using 3 945.00 kW of power, *Aurora* will consume 2.7 times more power and increase its productivity to 180 PFlop/s (18 times more).

New cooling systems, reducing the power consumption and nanotechnologies which create the element base, are widely used to increase the computing productivity of supercomputers. Currently, 22 nm (nm –one billionth of a metre) and 14 nm technologies are widely used in the development of microprocessors used in supercomputers. A number of transistors in microprocessors, developed upon these technologies, will equal to 2-4 billion. In coming years microprocessors will be developed on the basis of 7 nm and 5nm technologies. Computing productivity of supercomputers, based on these microprocessors, will equal to tens of EFlops (exaflops). It is impossible to reduce the dimensions of transistors in microprocessors following 5 nm technology [12, 13]. For this reason, new technologies (quantum, nanoparticles etc.) will be used to create microprocessors in the coming years.

Conducted researches show that the part of the power used in data centers is used for cooling of the system. Currently, three types of cooling systems are more widely used:

- *Air Cooling System*;
- *Water Cooling System*;
- *Immersion Cooling System*.

In air-cooling system, the cold air is supplied to the equipment through the grating of the raised floor and returns back to the conditioner from the ceiling of the room. This cooling system consumes 40-50% of overall power consumed by the data center.

In water-cooling system, water circulates in the pipes surrounding the entire system and cools the equipment. This cooling system uses 20-25% of the overall power consumed by the data center.

In immersion cooling systems, servers are immersed in dielectric liquid. This cooling system uses 3-5% of overall power consumption of the data center [14]. This system is relatively expensive in comparison with other systems. In spite of this, cooling system of the supercomputers in first three ranks of the supercomputer rating table of power saving supercomputers were created on the basis of the immersion cooling systems.

Majority of financial supply, necessary for placement and operation of supercomputers in data processing centers, are spent on supercomputer cooling systems. In order to reduce these expenses, application of Free Cooling Systems requiring low expenditure is considered in the near future. Data processing systems, developed on the noted cooling systems, will be mainly located in regions and countries with cold climate. Cost effective cooling systems will reduce the power consumption of data processing centers by 40% [10].

Iceland is expected to play an important role in data-center industry in the future. Several major companies are planning to locate their next data centers in Iceland. Iceland is planning to take important steps in order to develop this sector.

Supercomputer located at the ANAS Institute of Information Technology Data Center has 15 TFlop/s computing productivity and 300 TByte memory. Supercomputer renders electronic mail, Internet and hosting services for institutes and organization of ANAS. In addition, supercomputer is used to solve complex problems that occur in the institutes and organization of ANAS, and require large computing and memory resources.

Purposeful works are carried out in order to create a Supercomputer center at the Ministry of Communications and High Technologies of the Republic of Azerbaijan, and it is planned to put the center into operation in 2016.

Conclusion

Classification of parallel processing systems and architecture of supercomputers were analyzed in the article. Current status of supercomputer technologies and their distribution dynamics, based on different indicators. was analyzed. Development dynamics of supercomputers in the near future was studied. At the same time, use of supercomputers in data processing centers was analyzed. Issues related to use of new technologies for increasing the productivity of supercomputer and reducing the power consumption of supercomputers were reviewed.

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