Ensuring secure long-term data storage

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Abstract. In this presentation, technologies used to create long-term data storage systems have been reviewed. The objectives of long-term data storage systems of strategic importance for the development of society have been identified. It has been shown that network-based data storage systems (DSSs) are becoming a promising trend in this field. The most promising types of storage media that can be used to create long-term data storage systems have been identified.

Keywords: long-term data storage, optical media, network-based data storage systems, data migration.

1 Introduction

The problem of long-term storage of electronic documents is of high importance, having its impact on various fields of economy, science, and culture. While producing enormous amounts of data, modern society faces challenges related to organising systems for their storage, as well as methods for securing these storages against unauthorised access [1,2]. Ensuring secure storage of and access to data is an important element of an information security system [35]. The number of electronic documents increases drastically, and therefore, long-term storage will become even more challenging over time. The key challenges of long-term storage are: preserving the authenticity of a stored document throughout the whole storage period; ageing of storage media; inevitable updates of hardware and software storage environment; as well as the interpretability and presentation of stored electronic documents [3]. The following requirements apply to long-term data storage systems: a system for durable long-term storage of electronic documents has to be created and maintained, preserving all content-related and functional characteristics of source documents, as well as ensuring transparent search and access to the documents for users, for the purpose of both reading, analysis, and research [4]. As the body of knowledge available to humanity continue to expand, and so do data recording technologies, the importance of developing long-term storage methods increases [28]. Several types of data require continuous storage for decades, like archival storage, and even for hundreds or thousands of years, when dealing with ancestral data or data that can impact the survival of future generations [35].

2 Information Objects Requiring Long-term Data Storage

There's a growing number of information resources of strategic importance for ensuring informational security of both individual countries and international associations, containing data that require long-term storage. Some of these information resources are:

- Storing information related to complex engineered facilities. An example of such a system is the project for long-term storage of design and engineering documents (LOTAR – Long Time Archival and Retrieval). This project is considered a crucial work element in a number of industries involving products with long life cycle – architecture and construction, power industry, shipbuilding, and aerospace industry. The project goal is to develop common standards for all members of this international consortium designed to provide the capability to archive and retrieve digital product information. This applies primarily to 3D CAD (computer-aided design) and PDM (product data management) data that can be read and reused throughout the product life cycle, independent of changes in the IT application environment originally used for their creation. The multi-part standards created as part of the project cover both the information content and the processes required to ingest, store, administer, manage and access the information [5]. However, it is unclear from the open documents presented by LOTAR, to what extent this approach applies to the industrial equipment used in manufacturing processes. There's also no information on developing a specific archival medium that would suit the declared objectives.
- Storing data from routine environmental monitoring. These data are of special importance because of their crucial role in ensuring economic sustainability, therefore they are constantly used for servicing various industries, as well as the general public. For this purpose, data are routinely collected, analysed, and accumulated. These data are subject to official registration, long-term storage, and information services provided to various consumers. Data from hydro-meteorological monitoring in a given country can amount to hundreds of terabytes, and various media are used to store them [6]**.** Based on data from hydro-meteorological monitoring for long periods, hydro-meteorological or helio-geophysical phenomena, which due to their intensity, duration, or time of occurrence pose a threat to people's life and health or property, can be predicted with considerable credibility. The total worldwide economic losses from natural catastrophes and man-made disasters were USD 218 billion in 2010 (as estimated by *Swiss Re*, a Switzerland-based reinsurance company). According to the worldwide statistical data, the average annual increase in the number of dangerous natural emergencies is 4.0%, entailing a 10.4% increase in economic losses. Such specialised sets of data from hydro-meteorological monitoring for long periods are of special importance for emergency management agencies. The risks for economic activities arising from global climate change or major man-made accidents and disasters pose a significant threat to people and economic entities of different countries [7].
- Storing seismic tomography data for long periods. Archival seismic tomography data are valuable, because, when coupled with new data, they help in achieving

higher quality of seismic investigation results. Seismic tomography data are characterised by their high volume. Even a partial loss of data results in significant expenses for conducting repeated investigations. Current monitoring techniques can yield tens, and in some cases hundreds of terabytes of data per investigated area [8]. Seismic tomography has long been the primary method for oil and gas exploration [9]. Storing seismic tomography data for long periods and their comprehensive analysis can be highly beneficial for extraction works from current wells, as well as for exploring new reservoirs of liquid hydrocarbons. Long-term data storage in this case is ensured based on a combination of technologies – field data are archived on tape, while disk arrays are primarily used to store results of analysis [10].

- Storage of scientific heritage data, namely published results of scientific research and experiments, bibliographic and factual databases, information about scientists, their scientific activities, publications, projects, etc., as well as numerous unpublished documents such as reports, letters, memoirs, notes, photographs, etc. These resources are of great interest to the scientific community and general public [4]. Durable storage of research data is of great importance for further development of science [12].
- The storage and management of government records is a priority task in most countries of the world, including the US, the UK, and member states of the European Union. The U.S. National Archives today contain approximately 700 terabytes (TB) of electronic documents, of which 79 TB were acquired during the presidency of George W. Bush, and 250 TB – during the presidency of Barak Obama. E-ARK (European Archival Records and Knowledge Preservation) was co-funded by the European Commission under its ICT Policy Support Programme (PSP) within its Competitiveness and Innovation Framework Programme (CIP). The aim of the project is to ensure efficient record-keeping workflow related to the three main activities of an archive – acquiring, preserving, and enabling re-use of information. EARK is a multinational research project, which includes, except for archives, universities, ministries, foundations, and government authorities [13]. Creation of archives for long-term storage of legally relevant documents is of increasing importance, because, unless durable storage is achieved, documents with retention periods of 10, 25, 75 years or more could be impossible to digitalise. And if presented only in paper form, further work with such documents seems inefficient. Information from electronic archives will be available for use, intelligent search, knowledge retrieval, analysis and intelligent processing in expert systems, etc. [14].
- Storage of medical and biological information. Medical and biological information is extremely important for providing high quality services, as well as for preserving data on biological diversity. The amounts of medical and biological information subject to long-term storage are constantly growing. The volume of molecular genetic data presenting decoded genomic information subject to long-term storage exhibits especially drastic increase [15]. Today's medical research, including studying genetic bases of complex diseases, require comprehensive analysis of large sets of clinical information and molecular genetic data characteristic of individual

patient's organism. One of the most important computer databases of biological data in general scientific terms are global databases on the structure of biological molecules and genomes of various organisms, which contain a variety of information about living systems. The creation of computer databases of biological data, which contain various information about living systems, is a necessary tool for solving complex issues of assessing the biodiversity of individual regions, potential risks for it, formalising the assessment of their scale, and planning ways to restore and preserve biodiversity [16].

- Storing cultural heritage of humanity. Creating digital backup copies will help preserve cultural heritage objects in case of fires or other emergencies, as well as provide remote access to cultural heritage objects [2,17]. A separate challenge in preserving cultural heritage of humanity is preserving the languages of small-numbered peoples and ethnic groups [2]. Every people accumulates useful information about the world around and ways of solving specific problems of survival, existence, and development within its culture. Therefore, the diverse cultural heritage of small-numbered peoples and ethnic groups is valuable for modern society and should be preserved in order to prevent the loss of strategically important information.

3 Main Objectives of Ensuring Long-term Storage of Electronic Documents

In general terms, the problem statement for ensuring long-term preservation of electronic documents is as follows: long-term storage of electronic business documents needs to be ensured, securing the authenticity, interpretability (readability), and confirmation of authorship for a document, as well as the durability and disaster tolerance of the storage environment throughout the whole storage period [3]. The schemes of access to long-term archival storage differ significantly from those to general-purpose storage. Furthermore, data throughput and latency are of lesser concern for archival storage compared to ensuring consistence, integrity, and data security [32].

Traditionally, the problem of data storage has been solved by ways of increasing the capacity of storage devices using DAS (Direct-Attached Storage) architecture. DAS-based data storage systems are represented by external storage devices connected directly to server and used only by server. The use of multiple DAS-based data storage systems within information systems, as a rule, leads to the emergence of local storage systems distributed throughout the enterprise network. This makes expanding enterprise data storage challenging, since these systems don't support storage capacity sharing between servers and data distribution between them [1].

Lately, rapid development of distributed data processing methods and drastic increase in amounts of information accumulated in IT systems have led to radical changes in long-term data storage technologies. As requirements to storage capacity and data access speed increase, traditional approaches to storage no longer meet them [3]. The maximum capacity of storage devices, including those used for long-term data storage, is currently coming close to its physical limit, where the size of units of information is

comparable to single molecules [2,18]. Therefore, in recent years, increase in data storage capacities has been secured by means of parallelism technologies, i.e. designing network-based data storage systems (DSSs) [11].

The problem of increasing manageability, durability, and security of data storage and access, as well as the procedures of data transfer between applications and storage devices, has become pressing. Storage Area Network (SAN) is one of the most promising approaches to ensuring long-term storage of large data arrays. The main benefits of this approach are good scalability, high performance, and usability of SAN. At the same time, development and operation of SANs entail challenges associated with various aspects of security of stored information: accessibility, integrity, readiness, authenticity, and confidentiality. SANs can contain proprietary information of high value owned by different organisations or individuals. The most challenging situation in terms of data security can occur, when a part of storage capacities comprising a SAN is physically or logically lost, e.g., in case of major terrorist attacks, subversive actions, malicious intrusions, natural disasters, or errors of servicing personnel. In these cases, an important task is to study and develop methods of ensuring secure access to information contained in a SAN, meeting the following principal requirements: high performance and durability, utilising such benefits provided by SAN as parallelism and distribution of storage and processing functions [3].

The next step in the evolution of data storage is virtualisation and the use of cloud storage systems. Cloud storage services supplement and expand storage systems of a traditional data centre, while requiring zero investment in new equipment [33].

Long storage periods (varying from 70 to thousands of years) entail a pressing problem of organising an address system, which would allow some users to store information, and others to find and use it, even though the storage of and access to such information might be several generations apart. The primary challenge to be faced when designing such an address system is the structure of metadata. Without metadata, you cannot transform digital data (material level) into semantic data (ideal level). Moreover, metadata represents information about the location of data in space and time, their linkage with the user, and location on a storage device (spatial coordinates inside the device). Metadata are produced during the storage of information and are subject to routine management [39].

A set of organisational and technical measures should be in place to ensure preservation of electronic documents. These are creation of multiple copies placed in different geographical locations; the use of the checksum mechanism to control the integrity of a document; access differentiation and audit, antivirus protection; the use of recommended archival metadata standards and keeping metadata from the electronic documents preservation process; limiting the number of supported formats and migration to more stable formats as critical risks arise [37, 38].

Routine inspections should be carried out to secure digital storage devices against failures and physical degradation (at least once in 3-5 years), and information should be transferred onto new devices, if necessary. This operation should include data integrity checking and estimation of the remaining storage device lifetime. In case integrity checks reveal data corruption on a storage device, a new copy is created based on other copies of this information. Checking intervals are chosen based on the type of a storage

device, but in any case, for a read-only device (write once read many, WORM) they shouldn't exceed three years, i.e. once in three years each storage device should be checked and, if necessary, replaced. The process of transfer needs to provide for merging data from different storage devices, which is important due to growing capacity of storage devices of all types [19]. Data migration is an integral part of methodology for creation of long-term storage electronic archives. However, it is arguable, whether only documents from the database should be subject to migration, or also related metadata, classifiers, indices, etc. Classifiers and indices are integral parts of a document, since they define the context of its use: the subject area, organisational structure, storage and classification logics, relation to other documents, etc. Data loss during migration can be critical, leading to a document being viewed out of context of its use, which will complicate recognition of the subject area where it belongs. As information technologies continuously advance, the hardware and software environment changes, and all currently known electronic media rapidly become obsolete, it is impossible to preserve electronic documents without their conversion and migration. Solutions should be found to ensure their authenticity, integrity, fidelity and usability under conditions of long-term storage [12]. The primary method to preserve document authenticity is the use of an electronic signature. Long-term storage is associated with the problem of expired certificates (which are valid for a maximum of 5 years) and signature keys. It is recommended to use only encrypted qualified electronic signatures for long-term storage. Moreover, an electronic signature has to contain a trusted timestamp. Ideally, a certificate chain is incorporated into an electronic signature or transferred to an electronic archive with the signature. Only this can guarantee that the authenticity of a document will be traceable decades later, of course, if standards won't change and means to verify the electronic signature will still exist. To secure the authenticity of stored documents in an electronic archive, it is proposed to use an archival electronic signature, which will be automatically computed for all electronic documents placed in the archive [19]. Current long-term data storage technologies are based on the data migration method. When hard drives are used for long-term storage of information, it requires routine (once in 4-5 years) data transfer to new storage devices [19]. Data migration needs to include not only migration of electronic documents themselves, but also of document metadata. The long-term storage format description should be augmented with a set of tags needed to store document metadata (e.g. Qualified Dublin Core) [19]. The process of data migration is considerably complicated and expensive, and can entail partial data loss or modification. Therefore, storage devices with maximum possible migration intervals are preferable when creating archival storage systems [2]. Long-term data storage technology based on storage devices with short lifespan, which require frequent migration, is associated with high costs and doesn't ensure high storage durability [19].

Ensuring secure data storage is one of the most important features of a long-term archival storage system. Keys are widely used to encrypt information in order to ensure secure data storage. However, this method has several major drawbacks. Unfortunately, encryption with a key doesn't provide adequate data security, taking into account the lifespan of data stored in an archival storage system. Such encryption is based on computational efforts necessary to determine the key. Having enough time and computation

capacity, a key for a given data set can be calculated. Technical progress often reduces the time needed to obtain an encryption key drastically. When data are stored for decades or centuries, using encryption keys turns into a real problem [32]. On the other hand, using encryption for long-term data storage entails risks of losing the keys [30].

4 Analysis of Requirements to Media for Long-term Data Storage

The currently used common data storage technologies are not designed for long-term preservation. They are intended for use in real-time systems and provide for multiple modification of relatively small amounts of data, as well as their transfer to users through communication networks. The competitiveness of these systems relies on higher density of recording onto the data media and shorter reading/writing time (the developers also strive to reduce the time of access to data). Storage devices for such systems can be designed based on the years-long guaranteed preservation time, which is usually enough for real-time systems [35].

When considering types of storage devices for long-term data storage, the following storage intervals are distinguished:

1. Source data – up to one year;
2. Backup copies – 1 to 10 years;
3. Archived data – 10 to 100 years;
4. Data to be saved for future generations – possible storage time ranging from 100 to 1000 or more years [18].

Based on these requirements, types of storage devices for long-term data storage are determined according to their intended storage time. It should be noted that currently available storage media are not durable enough to store data for decades, let alone centuries. Moreover, due to technological obsolescence, in a couple of decades there will be no devices to read the currently available storage devices [2]. The lifespan of electronic documents stored in electronic archives is often longer than that of hardware and software. For instance, personnel records have to be stored for 75 years [3].

From analysis of today's technologies, it seems that producers of storage devices aren't much interested in long-term existence of any storage media. The estimated average lifespan of storage media production technologies, from their birth to almost complete disappearance from the market, is 10-15 years (magnetic tape, floppy disks, CD-R, DVD-R, etc.). Then new technologies displace older ones, and manufacturers wouldn't profit from supporting obsolete technologies [19].

When creating media for long-term data storage, two central questions emerge. The first of these concerns the material of storage media likely to last long enough to convey a message to generations thousands of years into the future. Throughout much of history, people carved important messages into stone, bone, or other hard materials. Faced with the lack of suitable options for storage device production, researchers around the world have re-embraced the use of chemically stable high-strength synthetic materials

as adequately durable long-term storage media. The Long Now's Rosetta disk, for example, is made of nickel. Arnano, a French technology start-up, has developed a disk of leucosapphire, on which to micro-etch information about the storage of nuclear waste. Hitachi announced a new data storage technology that uses quartz glass [28]. It should be noted that large-scale research is being carried out to create special long-term data storage media based on the use of highly stable materials and recording methods, which support different methods of reading. [2,21,22].

The second problem when creating long-term data storage media concerns the choice of the form for data presentation, which would enable their interpretation and use to obtain required information. When choosing data presentation form, not only technology is taken into consideration, but also the history of coding information for the purpose of knowledge transmission and preservation. What kind of 'code' will be most easily accessible to future generations, and what technologies will they have available to help them decrypt a message from the past? These questions of language and code are inevitably more difficult to answer than that of the storage medium. You can subject your chosen material to stress tests to make sure that it will stand up to acid, erosion, or any other kind of potential natural disaster. But there's no similar test for language: it's impossible to predict what codes will be interpretable by the people of the future, or what technology they'll have available to decrypt a message. The storage and transmission of data often requires multiple levels of encoding. Typically, two layers of encryption are used before we begin to digitise information. Spoken human language is itself a code, in which sounds are used to signify things or ideas. The use of a writing system adds a further layer of encryption: sequences of letters or pictographs signify the sounds that represent things or ideas. Yet another layer of encryption can then be applied by translating a writing system into binary numbers. These extra layers of encoding offer the advantage of increased information density. However, each layer further complicates the decodability and readability of a message. The Long Now project has proposed to store its data in the analogue form (human alphabet), rather than add an extra layer of encryption by a binary code [28]. To ensure high durability of long-term storage of information, noise-resistant codes are used. There's high interest to non-binary codes working with digital data on a symbol level, e.g. with bytes of information. Non-binary codes are used in channels with grouped errors as components of cascade codes to ensure error control on various types of optical media (CD, DVD, Blu-ray, etc.) [28].

It is proposed to record information on long-term storage media by means of placing diminished graphic or textual images onto the medium, which can be read by optical systems using appropriate magnification. The advantage of this way of presentation is that subsequent retrieval of information doesn't require special reading devices or software. The optical resolution required to read the data is defined by the diminution used for recording. Such data presentation is used on several types of sapphire and metal disks [2]. Presenting data as microimages complicates their processing and lowers the processing speed. Blu-ray disks intended for long-term storage incorporate redundant codes to ensure their quality [29]. These codes are inserted into the data area on the disk, separate from the customer's user data. When these codes are shown to the customers, they often say that it looks as if unknown data is inserted. A new method was

devised to insert redundant codes that conforms to the Universal Disk Format (UDF), an international Blu-ray Disc standard [29]. Piql microfilm uses data recording as QR-codes [2,25]. Since there is no universal type of large capacity long-term data storage device, long-term storage systems and archives are created on different media types. Long-term electronic archives use various types of storage devices. As no digital media can guarantee long-term data storage, microfilm with analogue recording method is widely used for archiving. When produced using modern materials and stored under specific conditions, microfilm can ensure data storage for centuries [22,23]. It should be noted that using photographic film with gelatine information layer is hardly an optimal choice for a noise-resistant and disaster tolerant storage medium. Choosing the best available long-term storage medium is quite challenging. The reason is that the choice is completely dependent on the area of application and customer preferences. Using two or three different storage devices is recommended in order to ensure maximum security [2]. In case one of them fails, the other ones will preserve the data. Special underground repositories like Barbarastollen (Germany), Granite Mountain Record Vault, Iron Mountain (USA), the Arctic World Archive on Spitsbergen (Norway) and more are created in order to store data on microfilm [2,24].

The following are examples of using different types of media to create long-term storage archives:

- Long term data storage systems are created based on hard disk drives. An example is ColdStorage run by Facebook. It is optimised in terms of energy efficiency and higher recording density, not performance or accessibility. To achieve this, magnetic drives are used, which are not intended for continuous operation, but allow changing disk rotation speed, increasing their number in one rack, and decreasing the number of simultaneously rotating disks. Due to the use of such storage technology, energy consumption per 1 exabyte disk array is about 0,375MW instead of 1.5MW [35].
- The robotised library on Panasonic optical disks established by Saint Petersburg State University can store data for 50 years or more [26]. Facebook proposes a significantly larger optical disk-based repository – this is an experimental repository comprised of 300,000 optical disks storing 30 petabytes of data. A specific disk with requested files is found by a robot. An optical storage system is projected to store up to 150 petabytes. Such system increases the access time to requested files significantly, however, its advantages are increased guaranteed preservation time and 80% lower energy consumption [35].
- Magnetic tape is widely used to store meteorological monitoring data [6, 7]. The European Organisation for Nuclear Research (CERN) Data Centre processes on average one petabyte of data per day. The Large Hadron Collider (LHC) experiments produce about 90 petabytes of data per year, and additional 25 petabytes of data are produced per year for data from other (non-LHC) experiments at CERN. Archiving the vast quantities of data is an essential function at CERN. Magnetic tapes are used as the main long-term storage medium, and data from the archive are continuously migrated to newer technology, higher density tapes [27]. For long-term archiving, tape storage offers tangible advantages over storage on on-line systems. It is ten times cheaper to store a gigabyte of data on tape than on HDD or SSD. The service

life of tape media is considerably longer, there are little or no hysteresis losses, and multiple error correction mechanisms can be used. Storing data on tape does not entail any energy consumption, and the high packing density means that only small quantities of material are required [31].

- Solid state devices are becoming increasingly used for archival storage. The use of SSD capacities considerably boosts performance as compared to traditional hard drives [34].
- The central repository of Germany's cultural heritage, located in a disused mine in Black Forest, uses microfilm to store data. Information is stored on 32,000km of microfilm (over one billion images). Records continue to be added to the archive at the rate of 1.5 million documents per year [24]. Microfilm is also the primary medium in the state system of insurance fund of the documentation of Ukraine. Modern microfilm, when stored in proper conditions, preserve its characteristics for over 500 years. For the purpose of long-term storage of archival fonds, special repositories are created, designed to ensure durable data storage [24].

Conclusions

1. Creating long-term data storage systems is a scientific and technological objective of high importance, having its impact on the progress in many fields of today's industry, as well as on the communication of knowledge to future generations.
2. Continuous increase in amounts of data subject to long-term storage and physical limitations of storage device capacities result in network-based data storage systems (DSSs) becoming the primary trend in creating long-term data storage systems.
3. When creating long-term data storage systems based on various architectures, special media for long-term data storage are used.

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