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Conceptual Framework of Integrated Technologies for Remote Sensing and Monitoring of Natural-Technological Systems

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Abstract. This paper describes an ongoing development of integrated technological framework for remote sensing and monitoring of complex systems containing natural, technological and social elements. The proposed framework provides computationally efficient and user-centered geospatial monitoring, analysis and modelling features based on heterogeneous information received from space and ground-based data sources.

Keywords: integrated remote sensing and monitoring, control, natural and technological objects, cross-border complex systems, systems architecture

1 Introduction

Nowadays, monitoring and control methods are applicable only for specific Natural-Technological Systems (NTS). As a result, statistical information about existing systems is not well coordinated. This drawback becomes more evident in emergency situations, when effective decisions must be taken within a short time period while different information flows have to be analysed (Merkuryev *et al.*, 2012).

The monitoring information regarding incidents and disasters is received typically from different data sources (e.g. biometric systems, aerospace systems, etc.), and, therefore, it is heterogeneous by nature (e.g. electrical signals, graphical, audio, video information, text, etc.). Thus, since modern NTS are very complex and multifunctional objects, their monitoring should be performed in conditions of large-scale heterogeneous data sets. Nowadays, the monitoring and control processes of NTS are still not completely automated.

This paper describes an ongoing work on the development of computationally efficient and user-centered geospatial monitoring, analysis and modelling framework that allows processing and integration of remotely sensed data at different spatial and time scales, as well as modelling and simulation for assessment of possible future development scenarios of the monitored and analysed natural-technological systems.

The goal is to improve integrated monitoring and control of cross-border complex natural-technological objects of Latvia and Russia within the INFROM project (Integrated Intelligent Platform for Monitoring the Cross-Border Natural-Technological Systems), ELRI-184 within the Estonia-Latvia-Russia cross border cooperation Programme within ENPI (European Neighbourhood and Partnership Instrument) 2007-2013. The target groups which are the final beneficiaries of the project are ministries and agencies of regional development; environment, geology and meteorology centres, departments of civil defence and emergency, local authorities, and academic and research staff of universities and research institutions.

In accordance to the Civil Defence Plan of Latvian Republic (The National Civil Defence Plan, 2011), the following main risk areas exist in the territory of Latvia where the application of advanced monitoring and control technologies is an essential task:

- Extreme weather conditions caused by storm, rainwater, snowfall, icing, blizzard;
- Water floods;
- Forest fire;
- Oil and oil product pipelines;
- Gas storage and regulation stations;
- National and regional high-risk objects that produce, use, manage or store hazardous substances;
- Hazardous substances leak;
- Nuclear power plants located closer than 300, 500 and 1000 km from the national boundary of Latvia.

Remote sensing can be used as a powerful basis technology for analysis, monitoring and control of all mentioned risk areas (Boyd and Foody, 2011).

2 Monitoring objects classification

For development of an integrated conceptual framework for remote sensing and monitoring of natural-technological systems it is necessary to classify the objects to be monitored. Generally, the objects of natural-technological systems for monitoring and control purposes can be divided into three main classes (Petuhova *et al.*, 2012):

1. Environmental and natural resources.
2. Natural disasters and industrial accidents.
3. Objects of technological systems.

2.1 Environmental and natural resources

Natural and ecological systems include the studies of the dynamics of ecosystems changes in varying degrees, study of the influence of various natural and anthropogenic factors on the ecosystem, evaluation of natural resource management regimes etc. Environmental and natural objects can be divided in two categories:

1. Monitoring of ecosystems (aerosols in atmosphere, air pollution, water pollution);
2. Monitoring of natural resources (inventory of agricultural land, yields forecasting, soil erosion, deforestation, forest inventory, rivers, lakes, seas ice cover, groundwater dynamics, water quality in rivers and lakes).

2.2 Natural disasters and industrial accidents

Monitoring of natural disasters and industrial accidents is related to analysis of the factors that precede and accompany disasters and accidents (Bhaduri *et al.*, 2008). The possible objectives there are the following:

1. Monitoring of emergencies associated with natural and anthropogenic impacts;
2. Simulation of emergency situations and prediction of their consequences;
3. Planning of emergency and rescue operations in areas of natural and anthropogenic disasters.

2.3 Objects of technological systems

Technological systems include variety of objects that are man-made or pertaining to a process or substance created by human technology. Technological system objects can be divided in two basic categories:

1. Buildings (energy production, factories and manufacturing plants);
2. Infrastructure (bridges, bus terminals, dams, pipes, railroads, roads, train stations).

Monitoring of technological objects allows observing changes in the monitored object in order to:

- Optimize processes related to the given object;
- Prevent events that lead to damage of the object;
- Determine areas affected by work of the object;
- Evaluate financial, ecological or other metrics of the given object.

3 Existing technologies and trends for monitoring of natural-technological systems

Methods used to produce traditional cartography seem insufficient when dealing with an emergency response that requires a higher level of dynamism in creation and dissemination of maps. In order to be really efficient in an emergency situation, those maps should contain as much as real-time information and up-to-date data. The decision, how fast should be performed acquisition of real-time information, is dependent on the concrete situation and emergency conditions. For example, in the emergency situation of spring inundation, the monitoring data availability within an interval of one hour is mostly sufficient and safe. However, in the case of wildfires or storms, the necessary data should be obtained at least within few minutes or even seconds.

Timeliness is crucial in the area of concern, and definitions of “trust” and “accuracy” significantly differ from those adopted in a traditional cartography. In the emergency situation, also data of unknown quality and with a low level of accuracy can play an essential role, even higher than pre-qualified data and maps. However, all the data should be correctly validated within the given situational context using as much as possible different data sources because untrue information can lead to negative or catastrophic consequences. Therefore, a new framework is necessary to be able to quickly and correctly integrate real-time observations including ones received from automatic and human sensors.

Technical models for monitoring of the natural-technological system objects are structurally similar to the conceptual models of these objects and mainly are determined by the monitoring objective. Thus it is impossible to describe all possible models and this paper describes several models for most prioritized issues.

The growth of natural and technological objects monitoring and control systems complexity and the increasing importance of uncertainty factors at all stages of monitoring and control systems functioning necessitate new approaches for control system construction.

The most perspective approach, namely, intellectual and intelligent control, has arisen within artificial-intelligence investigations (Russell and Norvig, 2010). The intellectual control systems as against to the intelligent ones are assumed to solve the problems of goal setting and model development. In such way new intelligent information technologies (IIT) extend traditional analytical and simulation modelling of complex technical objects. IIT use data-driven non-algorithmic computing with intrinsic parallelism and non-determinism.

IIT include (IEEE, 1996):

- Technologies of knowledge-based and expert systems;
- Fuzzy-Logic technologies;
- Technologies of artificial neural networks;
- Case based reasoning (CBR technologies);
- Technologies of natural-language systems and ontology;
- Technologies of content-addressable memory;
- Technologies of cognitive mapping and operational coding;
- Technologies of evolutionary modelling.

An application of IIT to monitoring and control of natural-technological systems introduces three lines of investigations:

- Development of modelling algorithmic, and informational tools for knowledge representation and processing;
- Development of knowledge-representation models in the interests of new intelligent information technologies;
- Construction of new applications accumulating results of two previous items.

The technologies for monitoring of natural-technological systems are based on the use of abstractions of the monitored objects in the form of conceptual, analytical or simulation models that can be categorized in two groups:

- Natural and ecological NTS models;
- Technological NTS models.

3.1 Natural and ecological NTS models

The monitoring of natural and ecological processes requires the use of endpoints and target indicators that can be measured and clearly understood by scientists, environmental managers, and the public. An important role there plays computer models allowing to develop hypotheses about system behaviour, as well as to interpret available data. There exist a big amount of methodologies, models and systems in the area of natural and ecological NTS. In this paper, the most important monitoring, analysis and modelling systems in the context of Latvia are described.

1) *Flood Mapping Systems*. Floods are the most frequent disaster type globally, and often also the most costly (CRED, 2011). The flood management can be considered

as a spatial problem. Flood mapping is tightly coupled with remote sensing and hydrochemistry, which combines the use of GPS and multispectral remote sensing for mapping the inundated area, chemical water sampling for distinguishing water sources flood and interpolation techniques, and geographic information systems for analysing spatial patterns.

The main tasks of the flood mapping systems are the following:

- Monitoring of a water surface;
- Control of ice conditions in a given region;
- Detection, monitoring and modelling of occurrence and dynamics of flood hazards and flood risk zones.

2) *Wildfire Monitoring Systems*. Forest fires play a critical role in landscape transformation, vegetation succession, soil degradation and air quality (Chuvieco *et al.*, 2010). Improvements in fire risk estimation are vital to reduce the negative impacts of fire; either by less burns severity or intensity through fuel management, or by aiding the natural vegetation recovery using post-fire treatments. The monitoring of forest fires usually includes detection of the thermal anomaly and controlling of the fire propagation. Fire sites can be therewith interpreted both visually and automatically (infrared spectrum), using radiance temperatures of thermal channels.

3) *Land Use Monitoring Systems*. The use of Earth science data, models and geographic information systems in agricultural monitoring and assessment continues to expand our ability to understand the impacts that climate variability, landscape change, and anthropogenic and economic forces have on global agricultural production. There exist large amount of methodologies and models for land-use modelling and monitoring systems, for example, CLUE land use change model (Verburg and Overmars, 2007), CSM-Cropsim-CERES-Wheat crop growth model (Ottman, 2008).

For land-use monitoring systems also can be useful Geographically Weighted Regression (GWR) or multi-level models, which sometimes is applied for tropical land use and cover change. GWR is becoming a more commonly used technique in urban geographical and environmental studies. The GWR is stated as (Fotheringham *et al.*, 2002):

$$y_i = \beta_{i0} + \sum_{k=1}^{n} \beta_{ik} x_{ik} + \varepsilon_i \, , \tag{1}$$

where β_{ik} is the value of the k th parameter at location i .

Based on the equation (1), the two-level random-intercept linear regression model is written as follows:

$$y_{ij} = \beta_1 + \beta_2 x_{ij} + \ldots + \beta_p x p_{ij} + \varsigma_j + \varepsilon_{ij} \, . \tag{2}$$

In different studies was defined a transformation on the near-infrared (NIR) and middle-infrared (MIR), with the aim of enhancing the spectral information in such a way that vegetated surfaces may be effectively discriminated and then ranked according to the water content of vegetation, leading to the distinction among green vegetation and burned surfaces. For these issues often are used different indexes in models: Burned Area Index (BAI) (Martin *et al.*, 2005), GEMI3 (Pereira, 1999), vegetation indexes NDVI or EVI3 (Libonati *et al.*, 2007).

4) *Systems for Automatic Detection of Coastline Changes*. According to International Geographic Data Committee (IGDC), the shoreline could be regarded as the most unique feature on the earth's surface. The location and attributes of shorelines are highly valued by a diverse user community; because they have never been stable in

either their long-term or short-term positions. Consequently, shoreline change detection and mapping are critical for safe navigation, coastal resource management, coastal environmental protection and sustainable coastal development and planning. One of the most interesting and valuable models for coastline change detection is model adapted for Darss-Zingst peninsula (Meyer *et al.*, 2011).

5) *Forest and Land Cover Change Monitoring System*. Forest damage caused by high wind speeds has during the past decades caused significant economic losses in forestry, both in central and northern Europe. In certain countries wind is the main abiotic risk factor in forests; therefore different special tools that help managers to assess the risk of wind damage are necessary. Different models can be used for such systems, for example, HWIND model is used to simulate data for the tree species-specific regression models and determine critical wind speed (Peltola *et al.*, 1999).

3.2 Technological NTS models

The technological objects and systems belong to the class of complex systems. Complex systems are systems that should be studied through polytypic models and combined methods. In some instances investigations of complex systems require multiple methodological approaches, many theories and disciplines, and carrying out interdisciplinary researches. Different aspects of complexity can be considered to distinguish between a complexity system and a simple one, for example: structure complexity, operational complexity, complexity of behaviour choice, complexity of development.

Examples of technological NTS models are:

1. Monitoring of cracks and bowing in structural walls;
2. Monitoring of soil undermining by burst water main;
3. Calculating the amount of available power for hydroelectric power station;
4. Calculating the amount of available power for wind farms;
5. Road wear.

4 Integrated conceptual framework

The conceptual framework of integrated technologies is based on actual results in the area of the theories of structure dynamics control, artificial intelligence, operation research, system theory, and system analysis.

Development of knowledge-representation based models, methods, and algorithms for monitoring and control of objects and for reconfiguration of monitoring system plays an important role in decision-making in the area of the main problems of synthesis and intellectualization of monitoring technology and systems for complex technical objects under dynamic conditions in real time. This task includes the following subtasks (Sokolov *et al.*, 2012):

- Development of methodological base for accumulation and use of ill-formalized knowledge about states of complex technical objects under "rigid" constraints (for example, real-time operation mode and recurrence of computational processes) applied to both process of knowledge accumulation and process of state estimation; development of methodological basics for structure reconfiguration of objects and of monitoring system (first line of investigation);

- Development of model-and-algorithmic basics for analysis and synthesis of reconfigurable monitoring system (second line of investigation);
- Development of new information technology for creation and maintenance of monitoring software and software prototype; approbation of the technology in typical application domains (third line of investigation).

4.1 Functional requirements of framework

Each application for remote sensing based monitoring of natural-technological systems itself has specific demands, for spectral (physical) resolution, spatial resolution, and temporal resolution. For a brief, spectral resolution refers to the width or range of each spectral band being recorded. As an example, panchromatic imagery (sensing a broad range of all visible wavelengths) will not be as sensitive to vegetation stress as a narrow band in the red wavelengths, where chlorophyll strongly absorbs electromagnetic energy.

Spatial resolution refers to the discernible details in the image. Detailed mapping of wetlands requires much finer spatial resolution than does the regional mapping of physiographic areas.

Temporal resolution refers to the time interval between images. There are applications requiring data repeatedly and often, such as oil spill, forest fire, and sea ice motion monitoring. Some applications only require seasonal imaging (crop identification, forest insect infestation, and wetland monitoring), and some need imaging only once (geology structural mapping). Obviously, the most time-critical applications also demand fast turnaround for image processing and delivery - getting useful imagery quickly into the user's hands.

The following main functional capabilities of the technology are required to provide monitoring of natural-technological systems (Petuhova *et al.*, 2012):

1. Image filtration (edge detection; smooth filters; speckle noise filtering; morphological operations; texture features calculation; noise removal; values interpolation);
2. Satellite data based thematic products (fire detection; clouds detection; snow and ice cover detection; land surface temperature calculation; possibility to set threshold values during calculation);
3. Thematic processing of radar images (radar images segmentation using specific algorithms; oil spills detection; possibility to get statistical probability of assessing the pixel as oil spill; ship detection);
4. Solar radiation balance calculation (capability to calculate short-wave radiation; capability to calculate long-wave radiation; capability to calculate air and surface temperatures);
5. Hydrological modelling (possibility to model hydrograph; flooding modelling; freshets and overflows modelling; acquisition of water distribution model on the specified date);
6. 3D modelling and visualization (cloudiness, fogs, mists, smoke modelling; water surface modelling; trees modelling).

4.2 Framework structure

The framework structure (Fig. 1) is oriented to support high performance user-centered computational platform. At the lowest component level, the goal is to effectively integrate all the available data with analytical capabilities from various geographically distributed data sources to enhance the reliability of the monitoring information and the speed at which it becomes available to decision makers.

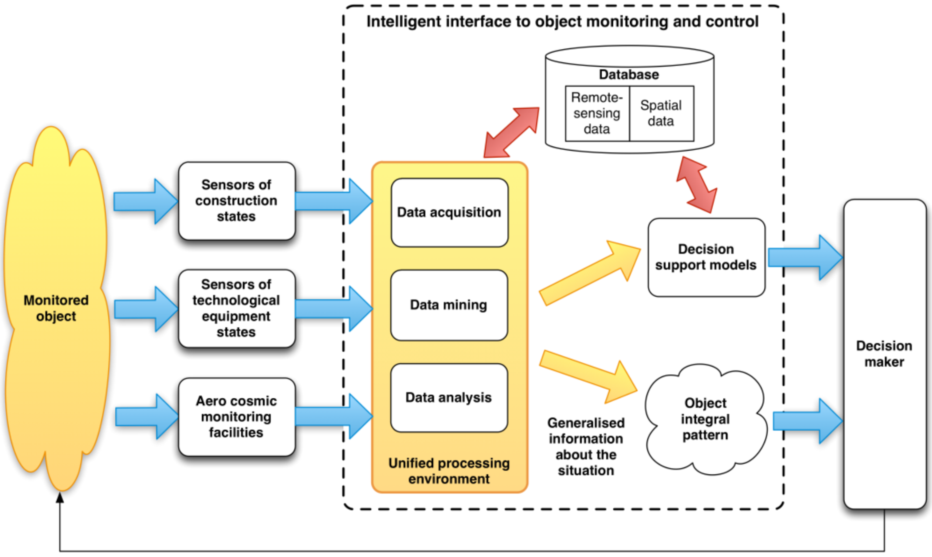

Fig. 1. General architecture of integrated remote sensing and monitoring system

Another important aspect is to provide the user with the most accurate spatial and temporal resolutions of data, model and tools according to the actual tasks to be solved. Consequently, assessment at different geographic scales should take advantage of different data sources.

The framework implements an unified approach to integrated monitoring and control of complex systems including natural, technological, economic and social elements and containing the following main components (Merkuryev *et al*., 2012):

1. Integrated real-time monitoring and control based on analysis of heterogeneous information from space and ground-based facilities;
2. Unified processing environment for processing heterogeneous data from different sources and their integration;
3. Distributed, real-time database embedded into the monitoring and control system for creating a common information space;
4. Multi-models for behaviour analysis of complex objects in normal and emergency situations and decision support;
5. Intelligent interface to object monitoring and control;
6. Data-flow computing models for large-scale datasets executed in real-time and in territorially distributed computer networks.

A key component of the conceptual framework is the unified processing environment implementing data mining, processing and analysis functionality. The processed data is used by the decision support component for modelling, optimization and visualization of the monitored systems.

The main problem of analysis and synthesis of monitoring and control system for natural-technological objects is a problem of correct and effective decision-making. The proposed framework structure lets combine analytical, simulation, and knowledge-based approaches for modelling, monitoring and control of natural-technological systems (Okhtilev *et al*., 2006):

$$\begin{aligned} &\left\{ \left\{Q^{(\xi)}\left(s,\Omega,F,\lambda_{\mu}\right)\right\}_{\xi\in\Xi_1}, \left\{\Delta_{\rho}^{(\xi)}\right\}_{\rho\in\Xi_2}, \left\{\Delta_{\eta}^{0(\xi)}\right\}_{\eta\Xi_3}, \left\{r_{i_1}^{\alpha(\xi)}\left(\omega\right)\right\}_{i_1\in\Gamma}, \right. \\ &\quad \left. \left\{r_{i_2}^{\beta(\xi)}\left(\omega\right)\right\}_{i_2\in\Gamma_1}, \left\{W_e\right\}_{e\in\Phi_1}, \left\{W_k\right\}_{k\in\Phi_2}, \left\{F^{k(\xi)}\left(\omega\right)\right\}_{k\in\Gamma_2} \right\}_{\xi\in\Xi_1}, \end{aligned} \tag{3}$$

where each mathematical structure $\left\{Q^{(\xi)}\left(s,\Omega,F,\lambda_{\mu}\right)\right\}_{\xi\in\Xi_1}$ defines some class of choice models (mathematical, logic-and-algebraic; deterministic or uncertain, etc.);

Ω is a space of events (the set of uncertainty);

F is a sigma-algebra over the space Ω;

λ_{μ} is a measure over $\left(\Omega,F\right)$;

$\left\{\Delta_{\rho}^{(\xi)}\right\}_{\rho\in\Xi_2}$ is a collection of the main basic sets of alternatives (each basic set corresponds to some mathematical structure $\left\{Q^{(\xi)}\left(s,\Omega,F,\lambda_{\mu}\right)\right\}_{\xi\in\Xi_1}$;

$\left\{\Delta_{\eta}^{0(\xi)}\right\}_{\eta\Xi_3}$ is a set of auxiliary alternatives to be used mostly in coordination choice tasks;

$\left\{r_{i_1}^{\alpha(\xi)}\left(\omega\right)\right\}_{i_1\in\Gamma}$ is a set of preference relations to be used for selection of the best alternatives via the structures $\left\{Q^{(\xi)}\right\}_{\xi\in\Xi_1}$;

$\left\{r_{i_2}^{\beta(\xi)}\left(\omega\right)\right\}_{i_2\in\Gamma_1}$ is a set of the relations defining constraints to be satisfied when an alternative is selected;

$\left\{W_e\right\}_{e\in\Phi_1}, \left\{W_k\right\}_{k\in\Phi_2}$ are constructions formed of basic sets via Cartesian products and generation of subsets (the first construction corresponds to the input scale of choice and the second one corresponds to the output scale);

$\left\{F^{k(\xi)}\left(\omega\right)\right\}_{k\in\Gamma_2}$ is a set of rules for constructing resulting choice functions and preference relations.

The monitoring data can be produced by different sensor platforms (satellites, aircrafts, land or water based) and consequently these data vary in spatial and temporal resolutions and internal structures. Integration of numerous heterogeneous data sources provides possibilities to unify and simplify the monitoring and control processes. Moreover, the proposed information technology will allow non-professional users to effectively use the integrated real-time monitoring and control systems of natural-technological facilities by lowering the usage complexity and by decreasing the necessary learning time.

5 Conclusions

This paper describes an ongoing development of integrated technological framework for remote sensing and monitoring of complex systems containing natural, technological and social elements. The monitoring of natural-technological systems is focused on the issues of changing ecosystems, geo-systems, climate and providing services for sustainable economy, healthy environment and better human life by the following activities:

- Early warning of natural and anthropogenic disasters;
- Technologic objects security;
- Land cover/land change, natural resource usage;
- Human health and the preservation of the environment.

Recent trends in information and communication technologies suggest that the described concept of technology integration using advanced information fusion and data processing methods provides a unified base for monitoring and control of different natural-technological objects. The further research is aimed at development of remote sensing based monitoring model prototypes to be applied into the integrated intelligent platform developed within the INFROM project.

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