AUTONOMOUS MONITORING OF MASONRY DAMS BASED ON MULTI-AGENT TECHNOLOGY

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Summary
This paper summarizes the results of a study investigating multi-agent technology deployed for decentralized, autonomous dam monitoring. Multi-agent systems, representing decentralized computing systems, have been used in artificial intelligence research for many years to tackle problems that are difficult or impossible to be solved by individual computational entities or by monolithic computer systems. In this study, a multi-agent system consisting of multiple intelligent software entities, referred to as “software agents”, is designed for decentralized, autonomous monitoring of masonry dams. The multi-agent system, implemented in terms of an “agent-based monitoring system”, autonomously collects and analyzes sensor data recorded from the dam, e.g. pore pressure, displacement, and temperature. The software agents are situated on individual computer systems to proactively solve monitoring tasks, such as data acquisition, data storage, data analysis, and automated generation of safety reports. The agent-based monitoring system is validated using sensor data recorded from a masonry dam in Germany. In this paper it is demonstrated that, compared to conventional monitoring strategies, the agent-based approach significantly enhances the flexibility and scalability of dam monitoring systems.

Keywords: Multi-agent systems, dam monitoring, agent-oriented design, structural health monitoring

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1. INTRODUCTION

Knowledge about dam safety under operational and environmental loads is of critical importance for dam engineers and vital for the well-being of the society, since structural failures may cause significant economic and life losses. The purpose of dam monitoring, commonly referred to as “dam surveillance”, is to provide assistance to dam engineers in assessing the static and dynamic behavior of dams in order to maintain and improve dam safety through uncovering anomalies in the structural condition [1]. By implementing and maintaining monitoring-based dam safety programs, life, property and the environment can be protected from hazards caused by dam failures.

Common causes of dam failures, among others, include (i) overtopping from inadequate spillway capacity or from spillway blockage causing erosion of the foundation (concrete dams) or of the embankment (embankment dams), (ii) leakage and piping in pervious strata, soluble lenses and rock discontinuities, and (iii) sliding in foundations [2-6]. Due to the safety importance of dams, several codes and guidelines exist worldwide providing detailed guidance on implementing monitoring strategies [1, 7, 8]. In Germany, the guideline DWA-M 514E (“Dam Surveillance”) embodies principles of dam monitoring and regulates structural assessment and data management of dams [9]. Conventional procedures for assessing the structural integrity of dams are based on visual inspections conducted by dam engineers, who recommend actions in case damage is detected. Visual inspections, according to [10], include thorough inspections of the conditions of dams and appurtenant structures, noting any abnormal or unusual conditions that could jeopardize the safety of the dam.

To complement the conventional procedures, most guidelines have been taking into account the rapidly evolving field of sensor technologies, which facilitates continuous, automated dam monitoring. New sensor technologies provide an improved basis to implement reliable monitoring strategies [11]. For example, correlated with environmental parameters, such as air and water temperature, sensor data is analyzed using statistical or deterministic models. Also, the dam behavior under vibrations caused by wind, water waves, or ground motion is evaluated using the sensor data [12]. Typically, modal parameters, i.e. resonant frequencies, damping ratios and mode shapes, are analyzed through forced or ambient vibration testing [13, 14]. The purpose is to maintain and improve dam safety by providing information used (i) for evaluating whether a dam is performing as expected and (ii) for issuing warnings if structural changes potentially endangering the dam safety are detected.

Because every dam is a unique structure, the minimum maintenance varies from visual observations of low-hazard-potential dams, to complex maintenance based on measurements of pore pressure, uplift pressure, surface movement, internal movement, and foundation deformation on large high-hazard-potential dams [10]. In other words, every dam monitoring system must individually be tailored to the dam structure being monitored, which requires dam monitoring systems being flexible and scalable. In this paper, a multi-agent system, being flexible and scalable, is used as a technological basis for dam monitoring. The multi-agent system consists of multiple intelligent software entities, referred to as “software agents”. The software agents, supporting autonomous data acquisition, data storage, data analysis, and automated generation of safety reports, are distributed on different computer systems to support the dam engineers and technicians. In computer science, software agents have been a matter of research for more than two decades [15]. An agent is an autonomous entity that, while communicating and interacting with other entities, observes its environment through sensors and acts upon the environment through actuators [16]. Evolving from the
field of distributed artificial intelligence, software agents are arranged in multi-agent systems able to control their own behavior in furtherance of their internal goals [17]. Goals of agents in a dam monitoring system may be, e.g., “data acquisition”, “data analysis”, or “report generation”. Intelligent agents may also learn or use knowledge to achieve their goals, promoting the flexibility and scalability of the multi-agent system.

This paper summarizes the authors’ research efforts towards autonomous, agent-based dam monitoring. In the remainder of this paper, the design and implementation of an agent-based monitoring system for masonry dams is presented, followed by a system validation using sensor data recorded from a reference masonry dam in Germany. The paper concludes with a summary and discussion. The interested reader is referred to previous studies, in which several aspects of agent-based monitoring are illuminated [18-28].

2. DESIGN AND IMPLEMENTATION OF AN AGENT-BASED DAM MONITORING SYSTEM

The agent-based dam monitoring system reported in this paper is designed for operating on masonry dams. The design and implementation of the monitoring system takes into account current guidelines that regulate instrumentation details and describe procedures for analyzing structural conditions of dams being monitored. The development of the monitoring system is based on [29] following the so-called Agent-Oriented Monitoring Systems Engineering (AGEME) development methodology proposed in [30], which supports the development of agent-based monitoring systems in five phases:

i. Requirements analysis
ii. Agent-based system analysis
iii. Agent-based system design
iv. Object-oriented implementation
v. System evaluation and optimization

The following paragraphs place strong emphasis on the design (phase iii) and implementation (phase iv) of the agent-based dam monitoring system. Drawing from use case scenarios, different types of software agents are defined, each holding responsibility for a distinct monitoring task. Thus, agent types include, e.g., sensor agents, data processing agents, data storage agents, and report agents [29], where each agent type provides one or more agent services. For instance, a “sensors service” provided by an agent of type “sensor agent” gives access to dam-internal sensors through remote access to the data acquisition units. The description of the sensors service is shown in Figure 1 in terms of an extended UML class diagram.

![Figure 1: Sensors service to access data acquisition units installed in the dam (source: [29], modified).](source)
The agent types are implemented into different computer systems located at the dam and at the offices of the engineers and technicians in charge of monitoring. As a result, a fully decentralized, agent-based dam monitoring system is achieved. Technically, the software agents are implemented in strict compliance with the standards on agent-based technology promoted by the IEEE Foundation for Intelligent Physical Agents (FIPA, [31]), using the FIPA-compliant Java Agent Development Framework (JADE, [32]). For agent communication, every agent operating in the monitoring system uses FIPA Agent Communication Language (ACL) and a common ontology to ensure a common understanding, facilitating the ability of the agents to interact and to exchange knowledge. In addition to interacting with each other, the agents interact with the users of the system, e.g. with dam engineers and technicians, through graphical user interfaces (GUIs).

From a software engineering perspective, the agent-based dam monitoring system is a decentralized system, i.e. a system whose components (agents, sensors, databases, etc.) are connected to spatially distributed computers. For example, data acquisition units installed in the dam to collect sensor data can be remotely accessed to analyze sensor data in near real time. Due to the distributed nature of the system, software tools or computer clusters for data analysis installed at remote sites can be easily incorporated into the monitoring system. Figure 2 shows the general architecture of the agent-based dam monitoring system. Because of the autonomous nature of the software agents, the overall monitoring strategy, including data acquisition, data storage, plausibility checks, data analysis, and report generation, is conducted automatically.

Figure 2: Architecture of the agent-based dam monitoring system (source: [29], modified).
3. VALIDATION OF THE AGENT-BASED DAM MONITORING SYSTEM

The agent-based dam monitoring system is validated using sensor data from a reference masonry dam located in Germany. The masonry dam, built in 1906, is a 51 m high and 320 m long arc-gravity structure instrumented with an array of sensors in accordance with German guidelines [9]. As shown in Figure 3, the sensor instrumentation includes two plumb lines and two inverse plumb lines, two inclinometers as well as 18 piezometers. Not shown in Figure 3 are 40 temperature gauges and a fiber optic sensor for temperature measurements.

![Sensor instrumentation of the masonry dam](source: [29], modified).

For validating the monitoring system, sensor data from the masonry dam recorded over 115 weeks is used. Specifically, air temperature and displacement measurements taken from the plumb and inverse plumb lines in two horizontal directions are used. Figure 4 gives an overview of the time histories of the aforementioned data sets. The following subsections exemplarily showcase the pro-active support of the dam engineers and technicians provided by the software agents of the monitoring system (i) in conducting plausibility checks on the sensor data recorded, and (ii) in analyzing the sensor data with respect to structural anomalies.

3.1 PLAUSIBILITY CHECKS

Plausibility checks are among the major responsibilities of the experts in charge of monitoring to be executed on a daily basis. The plausibility checks, autonomously conducted by the software agents using mathematical statistics, can be seen as a “pre-analysis” of the sensor data to provide the dam engineers and technicians a quick overview of the structural condition of the dam. The plausibility checks are performed by the software agents in intervals whose duration varies from one hour to one day depending on the safety relevance of the sensor data.
Besides pre-analyzing the sensor data, errors in the data sets (e.g. caused by failures in the measuring devices or sensors) are identified.

The dam engineers and technicians, through personalized user interfaces provided by personal agents, can remotely access the dam monitoring system to display or to analyze the sensor data. A personal agent serves as a “personal assistant” to the engineer that is installed on the engineer’s personal computer. Figure 5 shows a screen generated by a personal agent of the monitoring system that appears once a dam engineer has remotely logged in into the system. As can be seen from Figure 5, based on the pre-analysis of the sensor data, all measurements are within normal range (colored in green), except two plumb line sensor measurements (colored in red) that might indicate anomalous displacements; the plumb line sensor measurements, for validation purposes, have been manually modified by injecting measuring errors into the data sets.

![Figure 5: Personal agent screen of the monitoring system](image)

Figure 4: Sensor data used for validation (source: [29], modified).

### 3.2 DATA ANALYSIS

Figure 6 shows the real-time sensor data that is remotely called by the dam engineer to be analyzed, i.e. water level, pore pressure, displacement and seepage water. Visually, no indications of anomalous displacements are found, corroborating that the measuring errors manually injected into the data sets are the cause of the anomalies indicated by the plausibility checks. All sensor data can be further analyzed both automatically (by the monitoring system) and manually (e.g. by the dam engineer). Analysis techniques provided by the monitoring system include, for example, time series analysis, regression analysis and data mining.
techniques, such as cluster analysis. To further analyze the displacements of interest, a cluster analysis based on \( k \)-means clustering is executed. \( k \)-means clustering is a simple, yet robust, unsupervised learning algorithm frequently used in data mining for knowledge discovery in data sets. The goal of the cluster analysis is to group all data sets into homogeneous clusters, each cluster consisting of a water level, an air temperature, and a displacement measurement. The clusters calculated by the agent-based dam monitoring system are shown in Figure 7. As a result of \( k \)-means clustering, cluster 1 represents a typical load scenario of the dam in summer with a relatively low water level (300.39 m) and high air temperature (16.1°C), entailing relatively large displacement towards the water side (4.7 mm). Cluster 3 represents a typical load scenario of the dam in winter (305.16 m, 2.4°C, -2.3 mm), while cluster 2 represents the period between summer and winter, and vice versa (302.76 m, 10.5°C, 1.1 mm).

Figure 5: Automated plausibility checks, including pre-analysis of the sensor data (source: [29], modified).

Figure 6: Online information about water level, pore pressure, seepage water and displacement (source: [29], modified).
4. SUMMARY AND DISCUSSION

In this paper, a multi-agent system consisting of intelligent software agents has been proposed for decentralized, autonomous monitoring of masonry dams. Illustrative validation tests (plausibility checks and data analysis) have been shown, conducted using sensor data recorded from a masonry dam over 115 weeks. For validating the performance of the plausibility checks, measuring errors have been injected into the sensor data. The errors have been detected by the agent-based dam monitoring system. For validating the online data analysis capabilities of the monitoring system, automated cluster analysis has exemplarily been shown. The cluster analysis has unveiled three load scenarios indicative of summer, winter, and the periods between summer and winter, respectively.

It can be concluded that the agent-based dam monitoring system, through its personal agents situated on the computers of the dam engineers and technicians, pro-actively supports the human individuals in charge of dam monitoring. Furthermore, the validation tests have demonstrated that multi-agent technology can be advantageously used as a technological basis to design and to implement decentralized, autonomous dam monitoring systems, enhancing traditional monitoring strategies through increased flexibility and scalability.

Due to the technological advancements in computer science and sensing technologies, further improvements of the monitoring system can be made. Based on the experiences gained by the authors from previous studies, three areas of interest are recommended for further investigation, (i) wireless sensing technologies, (ii) mobile multi-agent systems, and (iii) fault-tolerant systems. Wireless sensing technologies, as compared to cable-based systems deployed for dam monitoring, are inexpensive to install due to the eradication of cabling cost. In addition, wireless sensor nodes offer computational resources that enable fully autonomous, decentralized execution of monitoring tasks. Given the safety-importance of dams, however, the reliability of data communication and power consumption, which are open research issues in wireless monitoring [33-35], still pose challenges in the adoption of wireless sensing technologies for dam monitoring. In order to efficiently use the restricted computational resources of wireless sensor nodes, mobile multi-agent systems may be deployed. In mobile-multi-agent systems, resource-efficient software agents are embedded into wireless sensor nodes, and software agents executing more complex (and more resource-intensive) algorithms migrate from computer systems to the sensor nodes only in case of potential anomalies in the sensor data [24-26]. An open issue that has not been adequately addressed is the occurrence of sensor faults, which may lead to miscalibrations, corrupted

Figure 7: Automated clustering of sensor data (source: [29], modified).
Fault-tolerant systems, known from avionics and electrical engineering, are capable of automatically diagnosing faulty sensors. Engaging fault diagnosis mechanisms in dam monitoring systems may enhance system reliability and data consistency [36-38].

5. ACKNOWLEDGMENTS

This research was partially funded by the German Research Foundation (DFG) under grant HA 1463/20-1. The results reported in this paper were mainly obtained by Dr. Ingo Mittrup during his work at the Institute of Computational Engineering at Ruhr University Bochum, Germany [29]. Dr. Mittrup’s valuable advice and generous support to this research is gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the DFG.

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