An abstract approach towards modeling intelligent structural systems

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Abstract

Current design standards have not kept pace with the rapid developments in intelligent sensing technologies. In modern engineering practice, engineering structures and structural health monitoring (SHM) systems are considered one entity, referred to as “intelligent structural system”, which is, however, not reflected in current design standards. Sensor data, obtained by SHM systems, provides valuable information about a structure throughout the life cycle, but sensor information provided by SHM systems is not considered in structural modeling concepts. This paper investigates the integration of sensor-based information into design and modeling concepts for intelligent structural systems on an abstract level. Since every civil engineering structure is built with a specific objective, the SHM system installed on the structure must be designed to maintain the specific objective. For example, stress concentration areas identified during the design of civil engineering structures should be observed by monitoring systems with respect to physical quantities of interest. Moreover, continuous validation of sensor data collected by SHM systems against corresponding design models involves coupling of structural models and SHM systems. Such coupling must be considered in the conceptual design phase. This paper presents an abstract approach towards modeling intelligent structures, with particular emphasis focused on coupling of structural models and SHM systems on a conceptual level. As a result, components of intelligent structures are described using an abstract algebraic approach, as illustrated on an intelligent structural system in laboratory experiments.

1. Introduction

Industrial progress involves evolution of civil engineering structures, which are not any more “simple” structures (“constructed and forgotten”), but rather sophisticated engineering systems equipped with modern monitoring tools observing and controlling the long-term behavior. So-called intelligent structures are examples of modern sophisticated engineering systems. According to [1], an intelligent structure is a structure that maintains and improves structural performance by recognizing changes in behavior and actions, adapting the structure to meet performance goals, and using past events to improve future performance. The adaptation to changes in behavior and actions is based on modern structural health monitoring (SHM) systems recording and analyzing measurements collected on the structure [2].

In a broader context, SHM systems in civil engineering are specific examples of cyber-physical systems. Cyber-physical systems are increasingly employed in several fields of science and industry for integrating the physical and the digital world [3]. Information is exchanged between physical processes and computational models, which are applied to describe the physical processes. In engineering applications, information exchange between physical components (employed to control the physical processes) and
computational models is automated through networking processes [4]. In general, cyber-
physical systems essentially consist of two subsystems, (i) a physical subsystem
(“physical domain”) comprising the physical processes and the structure itself and (ii) a
computational subsystem (“cyber domain”), which encompasses the computational and
networking processes. Measurements, originating from physical processes, are
transferred through networking processes to the computational subsystem, for data
evaluation. Based on the data evaluation, a controller sends signals to actuators installed
on the structure to eventually modify the actuator configurations, if necessary.

The coupled nature of cyber-physical systems puts specific demands on cyber-physical
system (CPS) modeling, because coupling between the cyber domain and the physical
domain must be taken into account at each step of the modeling process. In the context
of intelligent structures, the coupled nature is reflected in semantic coupling of SHM
system and structure. A successful robust design of intelligent structures requires tools
allowing adequate modeling of the coupled “SHM-structure” system. However, modern
design standards of engineering structures typically neglect the SHM part. Moreover,
since a SHM system must be taken into account in the design phase of intelligent
structures, modeling tools must provide a sufficient level of abstraction; otherwise,
conceptual modeling of the “SHM-structure” system will not be possible. However,
conceptual modeling methodologies facilitating abstract descriptions of coupling
between a SHM systems and structures have not been proposed so far.

Attempts to develop conceptual modeling methodologies supporting a high level of
abstraction to formalize modeling processes have been proposed by several authors. For
every, a strategy for model evaluation based on sensitivity and uncertainty analysis
has been illustrated in [5-6]. Although the strategy proposed in these studies supports
practical evaluation of models, the utilization of sensitivity and uncertainty analysis
significantly limits abstraction possibilities. In the CPS context, a conceptual modeling
approach has been proposed in [7], using set theory and abstract algebraic approaches to
describe components of a CPS and coupling between the CPS components. The
concepts introduced in [7] cannot be applied directly for modeling of intelligent
structures, because the focus in [7] has been related to a formal description of the
computational part of cyber-physical systems without allowing for complete
descriptions of intelligent structures. Finally, a conceptual category theory-based
modeling approach has been proposed in [8], where mathematical models (or physics-
based models) and coupling of these models have been discussed in detail. First
concepts about extending the results towards CPS modeling have been presented in [9-
10]. However, modeling of intelligent structures based on the category theory-based
modeling approach has not been done yet.

Because conceptual modeling of intelligent structures has not been addressed in full
generality, this paper proposes a generalized, abstract approach towards designing
intelligent structural systems. Moreover, a general architecture of intelligent structures
is discussed, emphasizing the challenges appearing in conceptual modeling of
intelligent structures. In particular, “building blocks”, whose combinations constitute
intelligent structures, are identified and discussed on an abstract level. Specifically, the
concepts presented in this paper are first steps towards developing a conceptual
modeling methodology for intelligent structures, which guides the complete modeling
process and describes the process structure on an abstract level. To fulfill this goal, an abstract algebraic approach is chosen as the core of a conceptual modeling methodology. Finally, conclusions are drawn, and the scope of potential future research directions is discussed.

2. Architecture of intelligent structures

In the upcoming discussion, intelligent structures are considered from the CPS perspective. The general architecture with a schema of interactions between the physical domain and the cyber domain in cyber-physical systems is shown in Figure 1. In Figure 1, the term “physical domain” refers to that part of a CPS, which physically exists, while the term “cyber domain” refers to the virtual part of a CPS.

![Figure 1. General architecture of a cyber-physical system](image)

Keeping in mind the CPS concept illustrated in Figure 1, Figure 2 shows a principal schema of an intelligent structure. In particular, the physical domain contains three basic objects, (i) the structure itself, (ii) a system of actuators installed on the structure, and (iii) a system of sensors as a part of the SHM system that inherently belongs to the intelligent structure. The cyber domain is represented by the term “model” referring to a general way of processing the measurements collected by the sensors and transforming the measurements to a control signal sent to the actuators.

![Figure 2. General schema of an intelligent structure](image)

According to the definition of intelligent structures introduced previously, an intelligent structure is a particular example of a civil engineering structure evolving during its lifetime. From the modeling perspective, the evolution requires specific consideration. Taking into account the principal schema of an intelligent structure shown in Figure 2, the evolution of two basic system components, i.e.
the evolution of the sensor system and
the evolution of the model,

must be addressed by conceptual modeling approaches. It should be noted that the structural subsystem related to actuators is excluded from the evolution process in this paper, because the installation process of actuators typically cannot be done by non-destructive methods, since actuators must be embedded into a structural system. Therefore, it is not completely clear if a structure after an actuator installation procedure, being complex and costly, can be considered as a next step in the evolution, or if it is an entirely new structure with unique modeling and design objectives. Thus, the proposed modeling concept considers changing and updating of actuator subsystems as a transition to a new intelligent structure, which requires conceptual modeling and instance modeling to be separated from each other (where “instance modeling” refers to the practical realization of conceptual models).

In contrast to actuator subsystems, sensor subsystems installed on intelligent structures can be easily updated with new sensors and validated by non-destructive methods. Particularly, wireless sensor networks are gaining increasing popularity due to low costs and simplicity of installation. Specifically, embedded computing is one of the most powerful tools offered by wireless sensor networks. A detailed review on the use of wireless sensor networks in SHM is provided in [11].

To address the question of the intelligent structure evolution and the corresponding aspects of modeling in more detail, the life-cycle phases of intelligent structures, (i) design phase, (ii) calibration and validation phase, and (iii) operational phase, are distinguished:

- **Design phase.** As any civil engineering structure, every intelligent structure is constructed with clear objectives that must be fulfilled during the operational life time. Therefore, design of experiments is of crucial importance in the design phase, because sensor subsystems as well as actuator subsystems must be designed to maintain the primary objectives of the intelligent structures. In addition, a detailed mathematical modeling of intelligent structures is unavoidable in the design phase, since sensor placement is closely related to the identification of critical points, such as stress concentration points, by means of a detailed modeling of the structures.

- **Calibration and validation phase.** The goals of this phase are general calibrations and validations of all systems of intelligent structures. Particularly, model calibration and model validation are one of the most important objectives of this phase. The fundamental law of model calibration and model validation is that different experimental setups must be used; otherwise, the model may be compromised. However, for time-dependent processes this law can be weakened by calibrating the model on a specified time interval and using the calibrated model to predict future behavior of a structure (validation process). Also, the calibration phase can be used to reduce future computational cost by substituting detailed and computationally expensive mathematical models via surrogate models built on measurements collected after testing the whole system.
Surrogate models, and data-driven models in general, have become popular in modern engineering applications, and particularly machine learning algorithms have been successfully applied to SHM [12]. Constructing data-driven models requires a considerable amount of data, which can be supplied by simulation results using mathematical models or by measurements recorded by SHM systems. Therefore, introducing data-driven models into the schema of intelligent structures is not possible before finalizing the calibration and validation phase.

- **Operational phase.** The operational phase is the final phase in modeling intelligent structures. The operational phase is characterized by continuous analyses of measurements collected by the SHM system, and by validation of these measurements against a model. The model may be a mathematical model, created in the design phase and calibrated/validated in the calibration and validation phase, or a data-driven model, created and calibrated/validated in the calibration and validation phase.

The life-cycle phases reflect general descriptions of the life time of intelligent structures. However, the proposed life-cycle structure can be adjusted to more specific phases and tasks. Taking into account the life-cycle phases, the challenges of conceptual modeling intelligent structures, summarized as follows, become evident.

(i) Conceptual modeling approaches must support changes to the model, e.g. by model calibration (model updating) or transitions from physics-based models to data-driven models.
(ii) Conceptual modeling of the SHM system must support the use of different, specific models utilized in wireless sensor network (WSN) modeling, such as game-theoretic models [13] or graph-theoretic models [14]. Furthermore, if the need for updating a sensor network appears during the life time of an intelligent structure, the corresponding conceptual model should support updates without a significant amount of additional work.

Keeping in mind the points discussed in this section, the abstract approach towards modeling intelligent structures is introduced in the following section.

### 3. Conceptual modeling of intelligent structures

First steps in the development of an abstract algebraic approach towards conceptual modeling of intelligent structures are proposed in this section. Originating from the general schema of an intelligent structure shown in Figure 2, abstract definitions of sensors and sensor networks are introduced. The algebraic constructions introduced in the abstract definitions are kept very general, according to the discussion in the previous section. The abstract definition of a sensor is introduced as follows:

**Definition 1 (Sensor).**
A sensor is the object $S = \langle I, Y, T \rangle$, where
- $I$ is a finite index set;
- $Y \in \mathbb{R}^N$ is a vector of measurements;
• $T$ is an $n$-tuple of specification information.
  Moreover, in the sequel it is always assumed that $I \leq N$.

The role of components $I$ and $T$ used in Definition 1 is the following:
- The index set $I$ is introduced to further use measurements, i.e. data and signal analysis. Particularly, modern tools, such as frame analysis [15], often address the concept of sparse reconstruction, i.e. taking not all measurements available, but only a subset of measurements. For the specification of a subset of measurements, the index set $I$ is needed. The condition $\text{card} \ I \leq N$ underlines that a partial selection of measurements is allowed.
- The $n$-tuple of specification information $T$ represents a standard information about the sensor (e.g. type, sampling rate, or unit).

Clearly, Definition 1 is bound to sensors measuring only one physical quantity. To cover multiple measurements, Definition 1 is extended as follows:

**Definition 2 (A refined definition of a sensor).**
A sensor is the object $S = (I, Y, T)$, where
- $I = (I_1, I_2, \ldots, I_n)$ is an $n$-tuple of finite index sets;
- $Y = (Y_1, Y_2, \ldots, Y_n)$ is an $n$-tuple of measurements with $Y_i \in \mathbb{R}^{N_i}$, $i = 1, \ldots, n$;
- $T$ is an $k$-tuple of specification information.

Moreover, in the sequel it is always assumed that that $\text{card} \ I_i \leq N_i \ \forall \ i$.

Upon introducing the basic definition of sensors, the next step is to define a sensor cluster (comprising sensor nodes) and a sensor network:

**Definition 3 (Sensor cluster).**
A sensor cluster is the object $B = (B, G, R)$, where
- $B$ is a sensor node or a base station controlling the sensor cluster;
- $G = (S_1, S_2, \ldots, S_n)$ is an $n$-tuple of sensors, introduced in Definition 2;
- $R = (R_1, R_2, \ldots, R_m)$ is an $m$-tuple of relations.

**Definition 4 (Sensor network).**
A sensor network is the object $\mathcal{S}N = (G, R)$, where
- $G = (S_1, S_2, \ldots, S_n)$ is an $n$-tuple of sensor clusters, introduced in Definition 3;
- $R = (R_1, R_2, \ldots, R_m)$ is an $m$-tuple of relations.

In Definition 3, the role of $G$, an $n$-tuple of sensors, is to take into account that a sensor node/base station $B$ connects and controls several sensors communicating under the supervision of the sensor node. The $m$-tuple of relations $R$ specifies the rules of communication between sensors. The specific form of these relations depends on the models used for WSN modeling. For specific examples of relations and practical meanings of the relations in WSN modeling, the interested reader is referred to [16-17].

It should be emphasized that a sensor cluster can be defined as a sub-element of a sensor network $\mathcal{S}N$, which is a standard model in WSN modeling. However, from the conceptual modeling perspective, such definition would require a more technical construction, since it is necessary to define the meaning of the inclusion relation $\subset$ for
objects that are not sets. For the sake of clarity, the technical construction is omitted in this paper.

Finally, considering the general schema shown in Figure 2, an intelligent structure can be formally defined as follows:

**Definition 5 (Intelligent structure).**
Consider the following abstract mappings:
- \( f \) – mapping of signals to measurements, i.e. this mapping represents a sensor;
- \( g \) – mapping of measurements to a control signal, i.e. this mapping represents a “model” processing measurement and sending a signal to actuators;
- \( h \) – mapping of a control signal to actions on a structure, i.e. the actions of actuators.

Through the abstract mappings, an intelligent structure \( \mathcal{I} \) can formally be considered as the following pointwise noncommutative composition:

\[
\mathcal{I} := h \circ g \circ f \quad \text{over } \mathbb{R}_+,
\]

where \( \mathbb{R}_+ \) denotes positive real numbers, i.e. the time line.

Composition (1) underlines that an intelligent structure is not just a “simple” structure, but rather a process composed of several basic components. Furthermore, the term “pointwise” illustrates that comparison and control of intelligent structures is done, in fact, not continuously in a mathematical sense, but rather at specific points in the life time of a structure. The frequency of evaluations of composition (1) depends on a general setting of the SHM system.

The concepts presented in this section are first steps towards developing a conceptual modeling methodology for intelligent structures. As has been demonstrated, the construction of intelligent structures by an abstract algebraic approach is implemented on a general level, but it can be specified for specific structures with clearly defined design objectives. In particular, by specifying models and tasks for WSN modeling, a specific form of relations \( \mathcal{R} \) appearing in Definitions 3 and 4 will be fixed. Moreover, a connection and adaptation of results related to the conceptual category theory-based modeling approach presented in [8] can be done in a relatively straightforward manner to achieve a higher level of abstraction, allowing a “simple” modeling of intelligent structures using commutative diagrams with a strong mathematical formalism behind each diagram.

### 4. Illustrative example

As a simple illustrative example illuminating the concept proposed herein, an intelligent structural system is designed and implemented in a laboratory experiment. The laboratory test structure is shown in Figure 3. The test structure is instrumented with three wireless sensor nodes (each wireless sensor node including one internal accelerometer), one base station, and one tuned liquid column damper (TLCD) equipped with an actuator controlling valve opening.
Figure 3. Intelligent structural system with tuned liquid column damper in a laboratory experiment

According to the concept introduced in Section 3, the general definition of a sensor is specified. Because wireless sensor nodes used in the laboratory experiment only measure single quantities without any additional requirements stemming from analysis tools, the general Definition 2 reduces to Definition 1. Thus, each sensor node installed on the test structure is characterized as follows:

1. The index sets $I_i$ are given by the natural numbering, $I_i = \{1, 2, ..., N_i\}$, for $i = 1, 2, 3$.
2. $Y_i \in \mathbb{R}^{N_i}$, $i = 1, 2, 3$ are vectors of measurements collected by each wireless sensor node.
3. $T_i = (\text{Sensor id, location, sampling rate, measurement quantity})$, $i = 1, 2, 3$ are 4-tuple of specification information about sensors (here: accelerometers).

Considering Definition 3, the sensor cluster installed on the test structure is given by

- the base station $\mathcal{B}$,
- $\mathcal{S} = (S_1, S_2, S_3)$, a 3-tuple of sensor nodes, specified above, and
- $\mathcal{R} = (R_1, R_2)$, a pair of relations, where

$$R_1 = \begin{cases} 1, & \text{if two sensor nodes are communicating,} \\ 0, & \text{if two sensor nodes have no communication,} \end{cases}$$ (2)

and

$$R_2 = \begin{cases} \text{id}, & \text{if } Y_i \subset Y_{\mathcal{B}}, \\ Y_i \cup Y_{\mathcal{B}}, & \text{if } Y_i \not\subset Y_{\mathcal{B}}. \end{cases}$$ (3)
with $Y_{\mathcal{B}}$ denoting measurements stored in the base station $\mathcal{B}$, and $id$ is the identity mapping. Relation (2) is a very simple model for communication, which is sufficient for the illustrative example presented in the laboratory experiment, and it can be easily extended to more complex models. For example, weights $\omega_{ij}, i,j = 1,2,3$, can be added to the model indicating the link quality between two sensor nodes. Relation (3) is a binary relation checking if all measurements have been transferred from a wireless sensor node $S_i$, $i = 1,2,3$, to the base station $\mathcal{B}$.

Finally, the intelligent structure $\mathcal{I}$ can be written according to composition $\mathcal{I} = h \circ g \circ f$ (Definition 5), where the mappings are

- $f: s \rightarrow (\mathbb{R}^{N_1}, \mathbb{R}^{N_2}, \mathbb{R}^{N_3})$ with $s$ denoting the signal recorded by sensors $S_1, S_2, S_3$,
- $g: (\mathbb{R}^{N_1}, \mathbb{R}^{N_2}, \mathbb{R}^{N_3}) \rightarrow t$ is a data processing mapping resulting in a trigger signal $t$ sent to the TLCD, and
- $h: t \rightarrow F$ is the mapping receiving the trigger signal $t$ and opening a valve of the TLCD by action $F$. For clarity, $h$ is simply referred to as an actuator installed on the intelligent structure.

Moreover, given that composition $h \circ g \circ f$ is performed at certain points in time, representing a pointwise evaluation in the sense of Definition 5, mapping $h$ can be specified further as follows

$$h = \begin{cases} id, & \text{if no damping necessary} \\ F, & \text{if damping is necessary} \end{cases} \quad (4)$$

where $id$ is the identity mapping.

5. Summary and conclusions

Intelligent structures become common in civil engineering due to their ability to maintain and improve structural performance by recognizing changes in behavior and adapting the structure to meet performance goals. The adaptation to changes in behavior and actions is based on modern SHM systems, widely employed in modern engineering constructions. On the one hand, sensor data, available through SHM systems, is a basis to provide valuable information on the structural life cycle; on the other hand, structural modeling concepts do not adequately consider sensor information provided by SHM systems. Specifically, abstract approaches towards designing intelligent structural systems have not been presented so far. In this paper, first steps towards developing an abstract approach for modeling intelligent structures have been presented. An abstract algebraic approach has been utilized as a basic tool for a general description of intelligent structures. Starting from an abstract definition of sensors and sensor networks, a principal structure of intelligent systems is derived. Moreover, the conceptual approach proposed in this paper is showcased on an illustrative example in a laboratory experiment corroborating that the conceptual approach, despite its conceptual nature, can be successfully applied in engineering practice.
Acknowledgements

This research is partially supported by the German Research Foundation (DFG) through grant SM 281/9-1. The support offered by DFG is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this paper are solely those of the authors and do not necessarily reflect the views of DFG.

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