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Paper:

Digital Twin of Artifact Systems: Models Assimilated with Monitoring Data from Material Microstructures to Social Systems

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In contemporary society, where changes in the environment surrounding artifacts as well as changes in the purpose and operating conditions of artifacts occur frequently, it is necessary to equip artifacts with resilience and plasticity, and to incorporate this knowledge in the succeeding generation of artifacts. For this purpose, we propose digital twin of artifact systems (DTAS) that focuses on structural materials, from their microstructure to the environment and social systems in which the artifacts are used. The realization of DTAS requires the development of modelling and monitoring technologies from the atomic scale to the social system, the development of technologies to operate these technologies in multiscale in an integrated way, and the development of technologies for model uncertainty assessment. In the future, the information on models and monitoring of artifact systems stored in DTAS is expected to be shared and utilized not only by designers but also among various stakeholders, contributing to the realization of a framework for co-creative development and consensus building through interaction between designers and users.

Keywords: multiscale modelling, inspection, adaptive development, service, co-creation

1. Introduction

There is no doubt that the artifacts that exist in contemporary society are the product of mankind's collective wisdom, and the quality of life has been improved by the benefits that they bring. This is because artifacts can provide a certain richness in artifact systems,[1] including interactions with society, organizations, and individuals, if their functions are designed on models created accurately for the artifacts to meet the needs of society and users and if the artifacts are manufactured and operated to demonstrate the functions [1].

However, the condition of the artifacts changes from moment to moment through use, and the elements that support their structure and operation degrade. In addition, the purpose and operational conditions of artifacts may be changed in contemporary society, where the environment surrounding artifacts is changing rapidly. It is often the case that artifacts with inferior safety and economic efficiency are used sometimes without being aware of the fact that their functions, which were thought to be optimal when they were first placed in service, have gradually degraded and become obsolete [2].

Safety-related risks have an increased probability of manifesting when they exceed design thresholds due to natural environmental changes, such as extraordinary natural occurrences, or due to unrecognized changes in daily use and environment. For example, huge earthquakes and extreme weather events expose artifacts to external forces that have not been anticipated before, increasing the likelihood of structural failure [3, 4]. These hazards and failures pose a threat to the sustainability of society, as the larger the scale of the artifacts that are deeply embedded in the society is, the greater the loss and damage caused by degradation and failure.

Furthermore, in general, once artifacts are designed and produced, ownership of the artifacts is transferred from the producer to the user. In the traditional sell-out business model, even if there is a gap between the user's demand and the function of the artifacts, the function of the artifacts in service will not be reviewed unless a failure or malfunction is reported by the user, and the loss caused by this gap will accumulate over time. In other words, the risks associated with economics may be overlooked over a long term.

In recent years, our highly digitalized society has made it possible to communicate and share information about various elements in artifact systems thoroughly and rapidly. The concept of acquiring a variety of information from physical reality in real space, using the acquired data to create a replica of the physical reality in cyberspace

1. In this paper, the term "artifact system" is used to refer to the environment and the social system surrounding the artifacts in addition to the artifacts themselves, which are individual engineering products.

with a model of the physical reality, and then making decisions based on the replica and feeding back to the physical reality to improve the efficiency of industrial and social systems, is attracting a lot of attention. This concept is called the CPS (cyber-physical system) or digital twin [5]. The latter is primarily used in the engineering field, while the former is used in a broader range of fields including science (e.g., medicine, social sciences, etc.). The contribution of such concepts or systems to the safety of artifacts is easy to understand. Furthermore, in recent years the fact that they support new business models, such as Rolls-Royce's Power-by-the-Hour, which charges for engine operation, or broad new business models such as outcome-based contracts, has motivated the integration of digital twins into artifact systems [6].

If the status of artifacts can be ascertained among designer, producers, and users during their service by using digital twins, it will be possible to consider appropriate operation and enhancement in terms of design and maintenance of the artifacts themselves from both the safety and economic points of view while considering the uncertainty. However, as discussed above, the risks involved with artifacts are to be determined not only from the condition of the artifacts themselves. Namely, it is necessary to consider the uncertainties arising from the interaction with stakeholders and the external environment surrounding the artifacts to properly understand the risks of the artifact system, and to consider sustainable operation [7].

Therefore, this study proposes digital twin of artifact systems (DTAS) as a broad concept that includes issues of risk that may arise due to the interdependent relationships of artifact stakeholders.

In examining the concept of DTAS and the necessary components of the system, this paper focuses on huge artifacts, i.e., bridges, power plants, ships, etc., in which the artifact frame, consisting of structural materials, is subjected to severe external forces and such that the failure of its safety and economic viability causes significant losses to society.

In the case of huge artifacts, even if they are exposed to catastrophic external events, the worst catastrophes can be avoided if they do not lead to the eventual destruction of the structural materials. In other words, it is possible to operate artifacts sustainably by always understanding the slightest signs that lead to major disasters at the material level, as well as simulating scenarios of unexpected events in parallel [8, 9]. Currently, the safety of structural materials can be consistently assured into artifacts through the use of computer aided engineering, a digital technology, during design and manufacturing. In addition, recent developments in computational and modelling technologies for strength analysis of structural materials have realized simulations of the atomic scale, and seamless integration with mesoscopic level and conventional macroscopic level to evaluate the integrity is also being realized [10, 11]. Similarly, information from nondestructive testing and monitoring in manufacturing and operation can be handled in a time-series manner using big data, and efforts to realize real-time and sustainable integrity evaluation are gaining momentum [12]. If the digital twin for evaluating the integrity of structural materials can be treated as a multiscale problem from both modelling and monitoring perspectives in DTAS, it will be possible to move away from macroscopic phenomenology and empiricism, and perform evaluation with minimized uncertainty.

Furthermore, the proposed DTAS deals with multiscale issues, including social systems, in order to minimize the uncertainty in the sustainable operation of artifacts and maximize their utility. For artifacts consisting of structural materials, DTAS is necessary for estimating the actual loads due to usage, and determining the magnitude and frequency of design loads, the threshold of integrity to be determined based on consensus, and the strength function to be provided, etc.

The paper is organized as follows. In Section 2, the basic idea of the DTAS concept, necessary technologies, and integration of multi-disciplinary technologies are described. In Section 3, specific efforts to build DTAS are introduced. We present the individual techniques that each author of this paper has developed and how these techniques are combined in DTAS. In Section 4, the significance and novelty of the proposed DTAS and its contribution to related fields are described in the discussion, and issues of dealing with multiscale phenomena, including social systems, and how to deal with them are discussed.

2. Proposal of Digital Twin of Artifact Systems (DTAS)

The original digital twin concept [13] that first appeared in the 2000s, was used in its early years chiefly in the aircraft industry and rocket development. To take the example of an aircraft engine, the purpose of studying it was to create a physical model of the structure of an engine, etc. on a computer, which is physically impossible to monitor constantly, and to maintain the model independently as a replica of the real engine while reflecting limited observational data in the model, for maintenance, research, and development. Recently, with the development of new technologies such as Internet of Things (IoT), sensors attached to devices feed back real-time usage information to a physical model on a computer, enabling online and bidirectional communication, and more advanced digital twin formats have been proposed and put into practical use in many industries [14–16].

The DTAS proposed in this paper is a concept that further expands the traditional digital twin framework and can be applied to artifact systems in general, including related stakeholders. However, in this paper, as the most important application of DTAS at this point in time, we focus on huge artifacts where a loss of safety in the structure would directly lead to a loss in the whole society and economy, and propose a specific technological configuration of DTAS. In the future, assuming the development of technologies for modelling the system control and use

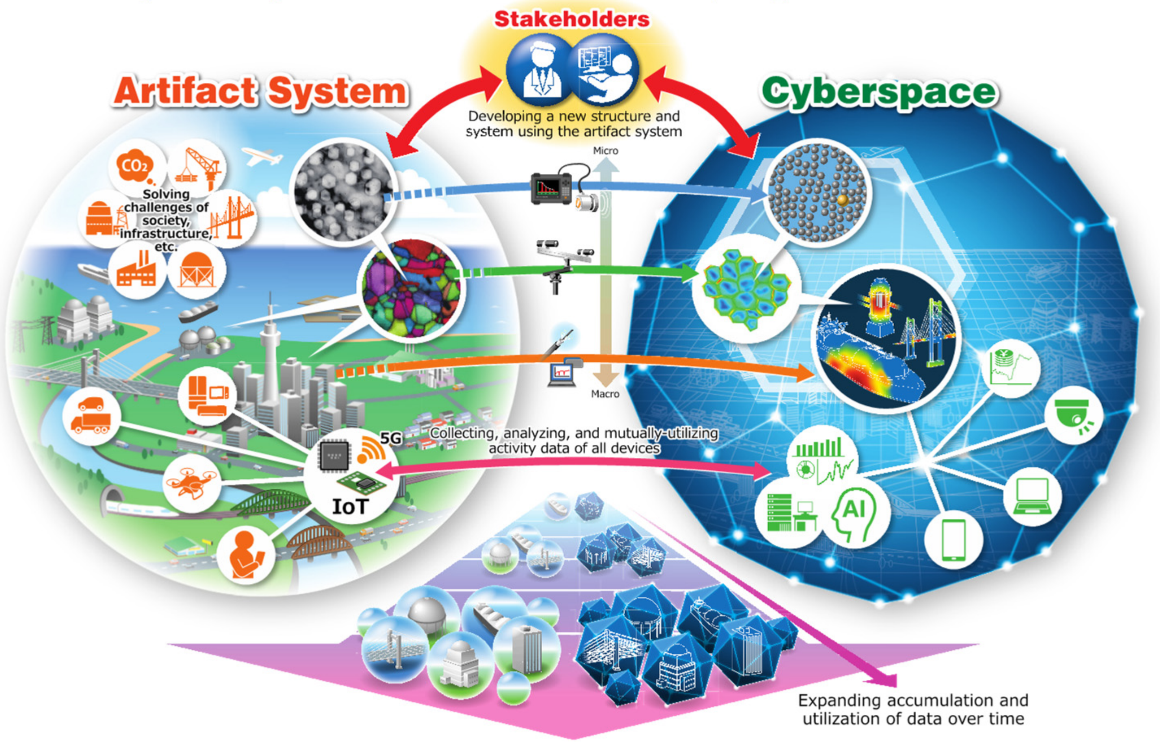

Fig. 1. Conceptual diagram of DTAS.

phase, it will be possible to realize DTAS with a technical configuration that can be applied to artifacts where elements other than structure are also important, by including the necessary technologies. It is a broad concept that aims to realize a framework for co-creative consensus building through the interaction between designers and users of artifacts by sharing models and related information of artifact systems stored in DTAS among various stakeholders.

2.1. Concept of DTAS

Figure 1 shows a conceptual diagram of DTAS. The left side of the figure represents the artifact system as a physical reality in real space, and the right side shows the corresponding image in cyberspace. This cyberspace is the DTAS that we propose in this study.

As can be seen from the figure, structural materials models from the microscopic level, such as at the atomic scale to the mesoscopic and macroscopic levels, are applied and kept as twins in cyberspace at all times. The artifacts will then be used in social activities, and their state will be measured by sensors and by other means. The information obtained is used as input to the models of each level, and the twins in cyberspace are updated from time to time [17].

In addition, as shown at the bottom of **Fig. 1**, the state of artifact systems in cyberspace will continually accumulate over time, and this information will be utilized in the design of the succeeding generation. The stakeholders depicted in the upper part of the figure represent the users of this DTAS, and the entities included in the actual target artifact system will use the stored data.

This is the overall picture of the proposed DTAS, which requires various elemental technologies in multiple fields. In particular, it is important for DTAS with a focus on structural materials that artifacts can be appropriately operated on the basis of micro-mechanisms rather than macroscopic phenomenology and empiricism, by multi-scale modelling and monitoring technologies that can take into account atomic-scale phenomena that are fundamental to the integrity of structural materials. This section gives an overview of the elemental technologies required for the implementation of DTAS and discusses the necessary requirements.

2.2. Collection of Knowledge from Multiple Fields

As in prior discussion of the digital twin, realization of DTAS requires the results of monitoring physical reality in real space and the preservation in cyberspace of models that behave as physical reality. However, the concept of DTAS proposed in this study includes models from the microscopic level, such as atoms in structural materials, to the mesoscopic and macroscopic levels, as well as the social system. This means that different research areas have been formed at different levels, which requires the integration of modelling and monitoring techniques (**Fig. 2**). This section outlines the basic modelling and monitoring methodologies in each field.

2.2.1. Microscopic Level

Changes in the properties of structural materials can be treated at their most extreme as atomic-scale behavior. A fracture is a change in macroscopic properties as

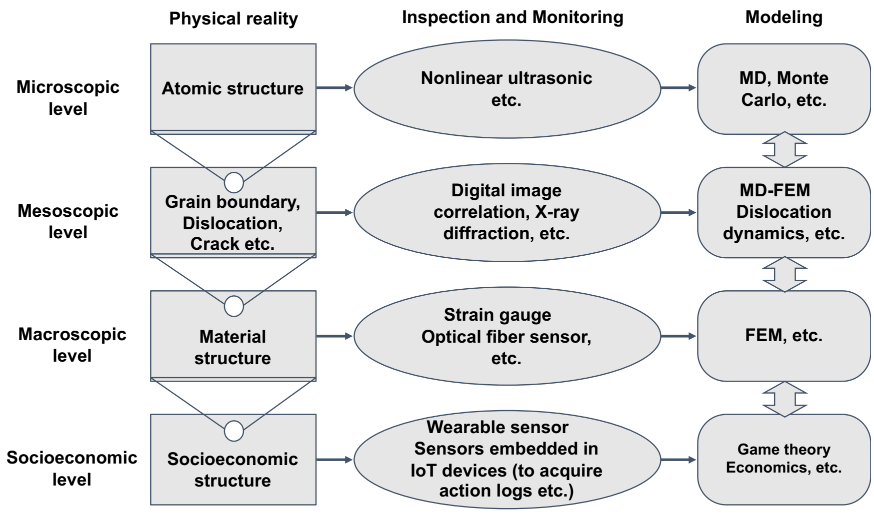

Fig. 2. Monitoring and modelling technologies at each scale.

a break in the crystal structure. Deformation is another change in macroscopic properties as a shift in an extra half plane [18–23]. From this point of view, the molecular dynamics (MD) method is an extremely valid method to describe material properties from the microscopic level. The MD method is a method to track change in atomic position and velocity in accordance with Newton's equations of motion, based on the interactions between atoms described by the atomic potential function. This method has been used to reproduce a variety of microscopic changes while maintaining a high degree of accuracy at the atomic scale [24–27].

Increased computational power has allowed us to handle considerably larger computational cells than in the past, and MD calculations are now frequently performed on systems containing 10^8 atoms or so. However, it is still impossible to reproduce an entire artifact on a very small scale of about 100 nm per side. Furthermore, it should be noted that even if we expect the improvement of the computational power, we need three orders of magnitude more computation to increase the size of computational cells by one order of magnitude.

Therefore, it is desirable to apply the MD method only to those parts of a structural material that are determinants of its life, i.e., those areas that have degraded particularly badly or are particularly important for safety. In addition, a technology for detecting microstructure using nonlinear ultrasonic as an input signal to the MD method is also being considered [28, 29]. However, such a microscopic inspection technique can only detect micro-signal changes in a relatively well-prepared environment and cannot necessarily provide a comprehensive picture of macroscopic material properties [30–33].

2.2.2. Mesoscopic Level

Following molecular simulations describing microscopic-level phenomena, there is a need for mesoscopic-level modelling focusing on crystal discontinuities, which are the bases of degradation in structural materials [34, 35]. At this level of modelling, it is not always necessary to treat individual microstructures at the atomic scale; fractures are treated as cracks, rather than as breaks in the crystal structure, and deformations are treated as dislocations rather than as shifts in an extra half plane [36, 37]. Similarly, crystal discontinuities such as crystal grain boundaries, surfaces, and interfaces with the second phase particle are treated as single objects, rather than being modelled from the individual atoms constituting them. A characteristic is that, by doing so, computational costs are significantly reduced compared to the MD method [38, 39].

The finite element method (FEM) and dislocation dynamics are typical mesoscopic-level calculation methods that focus on the spatial size scale. The FEM is a technique for obtaining solutions of overall behavior by dividing the part and area of interest into small elements without any gaps, and integrating the mechanical behavior models of those small elements. Dislocation dynamics is a method for decomposing dislocations, which affect plastic deformation, into segments and tracking their motion based on the elasticity theory. In multiscale modelling that needs to be kept consistent, FEM and dislocation dynamics are usually the links between the macroscopic and microscopic levels. In order to maintain consistency with the microscopic level, dislocation dynamics is combined with the MD method, which is based on a pre-determined atomic behavior that cannot be reproduced by elastic theory alone, to reproduce the phenomena. In MD-FEM analysis where the MD method and FEM are concurrently coupled, the MD method is used for the areas which require atomic-scale behavior evaluation such as a core area of dislocation or a boundary to the second phase particle, and ordinary elements are allocated to the other areas. Coupling the two methods concurrently is then used to reproduce mesoscopic-level behaviors [40].

Various inspection and monitoring methods are used depending on the input signals required for the model, such as digital image correlation for local strain detection and X-ray diffraction for residual stress detection. These methods detect the phenomena necessary to reproduce the degradation behavior of structural materials at the mesoscopic level.

2.2.3. Macroscopic Level

Various kinds of materials are processed in appropriate shapes and transformed into structured parts. In addition, when they are combined, they can function as the structural framework for artifacts such as machines and buildings. In order to understand and predict behavior at this level, it is necessary to consider not only the properties and functions of individual materials, which can be reproduced by modelling at the microscopic and mesoscopic levels, but also the functions of structural materials and their interactions at the macroscopic level. Namely, when the mechanical behavior of structural materials has been modeled, it is necessary to model the behavior when structural materials are combined into a structure, or to model the behavior of the entire structure consisting of the structure materials. From this point of view, FEM, which can model parts and structures as collections of small elements, seems to be the natural choice for a macroscopic-level modelling method. Macroscopic-level FEMs often use elements of the same order of size, or larger, than the entire mesoscopic-level model element. The method is widely used to model the mechanical behavior of parts, machines, and buildings, including both solids and fluids [41].

Various methods are in use for monitoring the behavior of a structure consisting of many parts, such as measurement of strain, temperature, and acceleration using multiple sensors, or a combination of remote sensing techniques such as laser surveying and thermal imaging [42–44]. However, because sensors can only measure local phenomena, it is necessary to interpret the results of measurement from multiple points in an integrated manner by means of the inverse FEM (iFEM), which is described below, in order to estimate the behavior of the entire structure [45]. In addition, it is not easy to maintain stable measurement throughout the service period of the artifacts due to degradation of the sensor itself and degradation of the adhesion between the sensor and the structural material. Although remote sensing can measure the entire surface of a structural material as a snapshot, it is not easy to continuously acquire time-series data or to measure a miniscule area inside a structural material.

2.2.4. Socioeconomics Level

Macroscopic-level description is the modelling of a large structure of artifacts, which reflects use phase. At a larger level, use phase can be a target to be modeled. A more general expression of the use of artifacts is that they cause a state change in the user by their functionality. It is in fact a service, and the field that creates and studies such state changes is called service engineering [46–48]. One approach is to break down the process of using artifacts and to describe the service process structure and the resulting changes in the user's state in a computer [49, 50]. There are also approaches that use wearable sensors and other tools to directly sense user behavior and analyze service delivery [51]. This is a necessary technical area to model the used part of the artifacts.

Furthermore, a simple one-to-one relationship between an artifact and a user is rarely complete, and the stakeholders surrounding an artifact are usually interdependent. In other words, it is a socioeconomic system. While it is the social sciences that deal with such subjects, the field that describes the structure of the social economy is economics. For modelling purposes, the economic sphere is formulated as the selection of products and services by people during their daily lives in a socioeconomic system. In addition, the criterion for choice is formulated based on the preferences that each person has. By nature, human preferences are subjective and difficult to model objectively. However, preferences have been effectively modeled as binary relationships, which successfully resolves the problem of subjectivity. Any preferences can be defined for ordering. Inconsistent rational preferences are formulated using the properties of reflexivity, transitivity, and completeness as axioms. The utility function expresses a real number applied to a preference, and its magnitude is not significant. The theory of market equilibrium, in which supply meets demand, considers a demand function that is derived from the accumulation of individual preferences, which in turn determines an equilibrium price. It should be noted, however, that this is a theoretical system that assumes the maximization of individual utility functions, and is not a theory that describes the real economy and society as they are.

Game theory [52] is also important in modelling socioeconomic systems. Again, the idea of preferences and utility functions is fundamental here. Moreover, the field of mechanism design [53], which applies game theory to social institutions and other systems, has been formed, where social institutions and rules are formulated in a generalized form of mechanisms. This is a field that assumes that entities behave rationally, and aims to design mechanisms such that as entities self-interestedly pursue profit, the sum of their actions will produce a state desirable for society as a whole. Thus, it is possible to apply the findings of the social sciences to modelling, and it is expected that the social structure will be described on the DTAS proposed in this study.

Behavioral economics, on the other hand, studies people's decisions based on actual human behavior. For example, the prospect theory by Kahneman and Tversky [54] offers an explanation for human behavior that cannot be explained by the model of rational preferences assumed in conventional economics. In addition, in the field of behavioral economics, there is much prior literature on various intrinsic cognitive biases among people, and a large amount of knowledge on human intrinsic behavior in using artifacts has been accumulated. Such knowledge can be applied to the DTAS in the future.

2.3. Necessary Performance and Requirements

2.3.1. Inspection and Structural Evaluation of Artifacts

An inspection system that provides real-time status of artifacts is one of the key components of DTAS. In Section 2.2, the basic technologies for inspection and structural evaluation were described, and these include macroscopic inspection techniques to detect the progress of degradation of structural materials in a wide range of areas, and microscopic inspection techniques to detect the progress of degradation in particular areas based on the results of the macroscopic inspection. By utilizing them, the degradation of structural materials can be properly assessed.

Furthermore, it is expected that the development of a numerical model that can calculate structural material degradation using real-time inspection/monitoring data at each of these levels as input values, and multiscale analysis that can concurrently couple these models, will enable us to reproduce or accurately predict the state of the structural materials in cyberspace.

In this way, it is essential to combine macroscopic and microscopic inspection and monitoring (hardware) with numerical analysis models (software) in order to construct a virtual twin in cyberspace that reflects to a high degree temporal and spatial information about the integrity of actual structural materials.

2.3.2. Resilience and Plasticity of Artifacts

If the evaluation of the behavior of structural materials described above could be continued by DTAS during service, it would be possible to enhance the artifact system during service. For example, if the progression of degradation of existing facilities can be continuously evaluated, the inspection timing and operation plan can be optimized. If it is possible to detect vulnerable points in advance by stress tests in DTAS, it will be possible to reduce the risk of the artifact system in advance, even in the consideration of cases where the structural materials are subjected to unexpected loads caused by external factors such as natural disasters. In addition, in case of occurrence of severe accidents, measures can be proposed to prevent a catastrophe if changes in the properties of the structural materials can be instantly understood by reproducing actual loads in DTAS. Thus, the construction of DTAS is expected to improve the toughness (resilience) of the artifact system. Furthermore, even in the cases where the purpose and operating conditions of artifacts change due to changes in the environment surrounding the artifact system, such as changes in social structure and demand, artifacts can be given plasticity by clarifying appropriate changes in the form and specification of artifacts using DTAS to enable flexible operation.

These operational insights gained by DTAS can be an important source of information for alternatives to current safety management standards and codes, such as internal and external maintenance standards, which inevitably prescribe conservative management criteria, to provide options for more rational decisions. This will enable significant cost and efficiency improvements, as well as revolutionary design changes, without requiring a large amount of material consumption and time for the development and commercialization of succeeding-generation artifacts.

One of the major features of DTAS is that it enables safer and more efficient operation of artifacts by taking into account environmental changes, which was not possible with conventional system maintenance that evaluated the timing and location of inspections using a predictive model for structural materials [17].

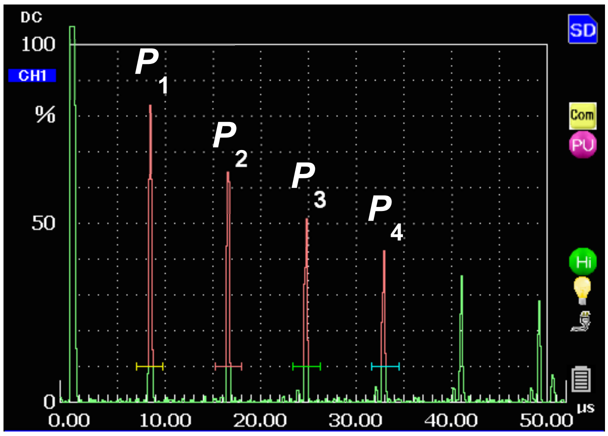

Fig. 3. Ultrasonic signal at 10 MHz.

3. Individual Element Technology Constituting DTAS

3.1. Microscopic Level

As indicated in the previous section, it is necessary to understand and reproduce the behavior with atomic-scale precision at locations where the degradation of structural materials is particularly advanced, which may be a determinant of their lifetime, or at locations that are particularly important for safety. However, the technology for direct observation of microstructure with such a high resolution is currently not practical. Therefore, in this section, an ultrasonic technique for indirectly detecting dislocations, which are the microstructure responsible for plastic deformation, is introduced for steel materials, which are widely used as structural materials.

The specimen preparation method has been presented in detail in a previous study [17] and will be presented here briefly. Since the Fe-3% Al alloy used as a test specimen is a transformation-free steel, coarse-grain specimens that can be used for ultrasonic tests were successfully obtained by keeping the material at a high temperature and allowing their grains to grow sufficiently. This made it possible to nearly eliminate the influence of crystal grains, which are strong scatterers of ultrasonic. **Fig. 3** shows the ultrasonic signal obtained at a frequency of 10 MHz. P_i ($i = 1, \ldots, 4$) in the figure shows backwall echo measured after going and returning i times through the specimen.

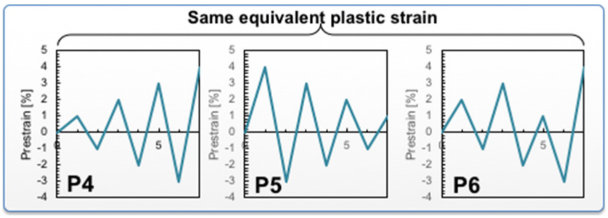

Fig. 4. Three kinds of pre-strain loaded in the present model [61].

Namely, the difference in the amplitude between P_{i-1} and P_i corresponds to an attenuation due to the interactions with a microstructure (dislocation structure in this case) during the i-th propagation of the ultrasonic through the specimen. A microstructural quantity (dislocation density in this case) can be estimated by obtaining this attenuation at multiple frequencies.

Changes in mechanical properties such as increase in the yield stress can be quantified if the dislocation density obtained by the microscopic inspection technique is used as an input value for the MD method [55–57]. As we demonstrate in the next section, this technology contributes to the establishment of DTAS as a source of input to the mesoscopic-level model, by detecting the increase in dislocation density as a driving force for the onset of brittle fracture and fatigue damage.

3.2. Mesoscopic Level

External loads on equipment and structures often alternate between positive and negative, and can be random, as represented by waves and earthquakes. In addition, the areas where critical damage such inspection as fatigue and fracture begins are often areas with geometric stress concentrations and stress concentrations resulting from welding thermal stress. However, it is known, for example, that conventional damage accumulation evaluation methods, such as those presented in the Miner's rule [58], give overly conservative evaluations in the case of repeated positive and negative alternation loading. It is extremely important to improve the accuracy of damage assessment in DTAS. For high accuracy, mesoscopic-level modelling is necessary along with the damage mechanism. Taking the brittle fracture of steel as an example of damage morphology, it is known that the initiating driving force is pile-up dislocations at a boundary between a second phase particle in the grain boundary and the matrix [59]. The authors established a computational method for estimating the amount of damage by extending and applying the method of conventional mechanism-based strain gradient plasticity [60], which can accurately estimate these mechanisms with moderate computational burden, to commercial FEM software (**Figs. 4** and **5**) [61].

3.3. Macroscopic Level

Structural health monitoring is the foremost technological concept for monitoring the behavior of artifacts in

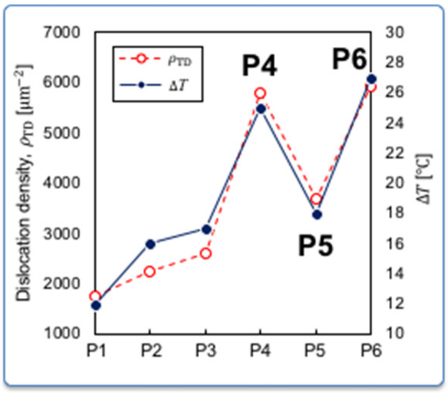

Fig. 5. Pre-strain condition dependence of the temperature shift ΔT in the limit transition curve of the crack tip opening displacement and the maximum dislocation density at the grain boundary [61].

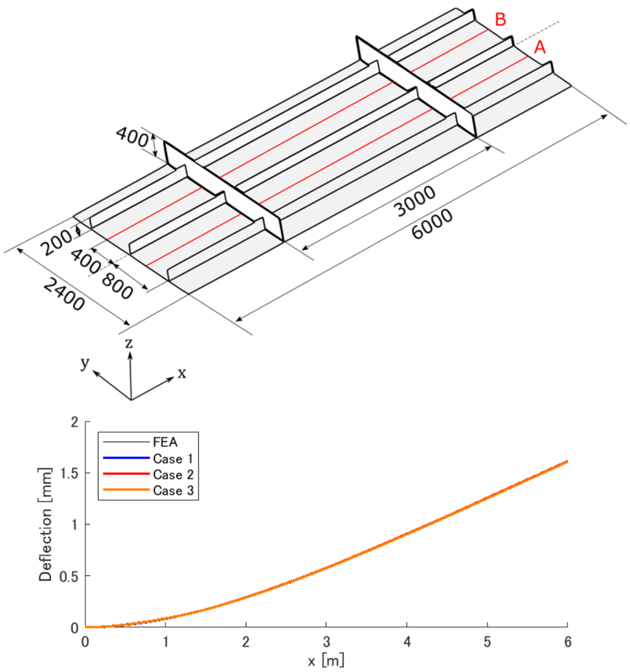

Fig. 6. Displacement of reinforced board estimated by iFEM [65].

real-time, at the macroscopic level, from a structural point of view. It is designed to detect damage and optimize inspection and operation of the system by determining a quantity related to structural integrity from output of sensors integrated into the structural material, and comparing the quantity to a specified value or threshold [62]. For example, a velocity response spectrum is obtained as a state quantity from an accelerometer output, and indexed as SI (spectral intensity) value. When SI exceeds the predetermined limit value, operation is stopped or a detailed inspection is performed [63]. The authors also successfully developed iFEM to determine the displacement of a structure based on the strain output from a fiber-optic sensor as shown in **Fig. 6** [64, 65]. It is possible to re-

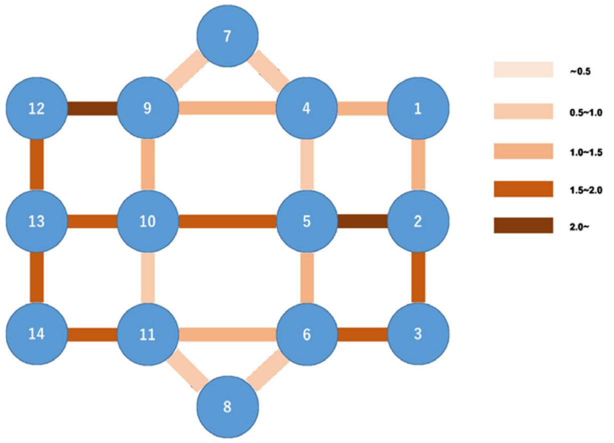

Fig. 7. Simulated traffic volume.

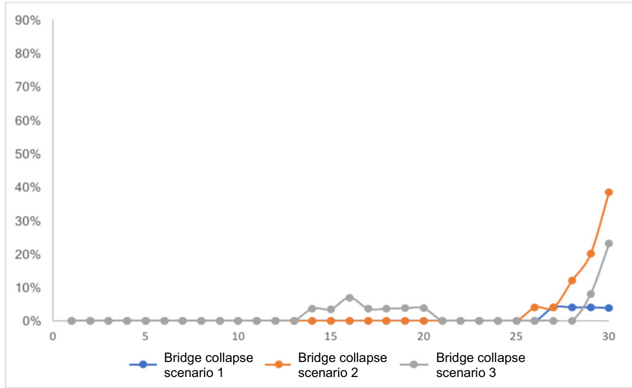

Fig. 8. Probability of bridge collapse with no repair.

construct the stress distribution of the entire structure, including unmeasured points, by giving the displacement as a boundary condition of the FEM, and we can evaluate damage evaluation more accurately by providing the information such as the displacement as nominal stress to a mesoscopic-level model. On the other hand, if a history of operational conditions and future projections are obtained from the socioeconomic-level model, it is possible to estimate loads and other information that can be used as inputs to the macroscopic-level model.

3.4. Socioeconomic Level

We here introduce studies on modelling and simulations of artifact-using situations and social systems including artifacts [66, 67].

Taking a bridge as an example of an artifact, we consider the situation in which residents of the surrounding area use the bridge in their daily lives. On the basis of the assumption that the residents, entities in action, can benefit by moving from one point to another, a utility function is defined for each of the entities. The residents use the bridge during their movements. In this study, a machine learning algorithm is incorporated and the behavioral principles of each entity are formulated in such a way that the behavior with the highest utility function (path selection) is acquired. At the same time, the structural materials of bridges are assumed to degrade due to their use. In the present study, for simplicity, the degradation is incorporated into the model as being proportional to the amount of traffic. A model of a simple lattice-based road network structure was created as an artifact containing a bridge.

An example of the simulation results is shown in **Figs. 7** and **8**. **Fig. 7** shows the results of the simulation of the case where the bridge at the center of the grid has the highest traffic volume. **Fig. 8** shows the result of simulating how likely each model bridge would be to collapse if no maintenance is performed on the bridge at all. We see that the probability of collapse of the bridge over the grid center with heavy traffic has increased.

Although this simulation is a trial simulation of a bridge, it could be one of the key technologies for DTAS to maintain and simulate in cyberspace models of actual social structures, with inputs such as data from sensors embedded in artifacts, as well as data on human behavior.

4. Discussion

This section discusses the novelty of the proposed DTAS concept, the efforts required for its implementation, and the problems to be solved before implementation.

4.1. Multiscale Synthesis

Although the elemental technologies described in Section 3 can be established as one independent study in their respective fields, the technologies of different scales must be integrated to implement DTAS. However, since the governing equations are completely different at different scales, it is usually difficult to consistently analyze and couple them together. Although there have been examples of coupled analyses of systems focusing on specific events (e.g., [68, 69]), concurrently coupled models that comprehensively treat phenomena between different scales, including these models, are not yet complete.

On the other hand, the proposed DTAS is unique in that it includes the MD method, which is an atomic-scale analysis method. When computational power does not need to be set as a constraint to the analysis, the entire artifact can be recreated using atomic-scale MD methods, and very precise twins can be stored in cyberspace at all times. However, due to the limitations of computational power, even the current MD method is forced to target only very small areas. In other words, for the parts particularly important for improving safety and ensuring reliability of an artifact, the MD method is used to perform highly accurate simulations. The method of mesoscopic-level modelling is used for the parts that do not necessarily need to be analyzed so precisely and can be approximated. In doing so, the results obtained by the MD method can also be data to use as higher-level inputs. This allows the model

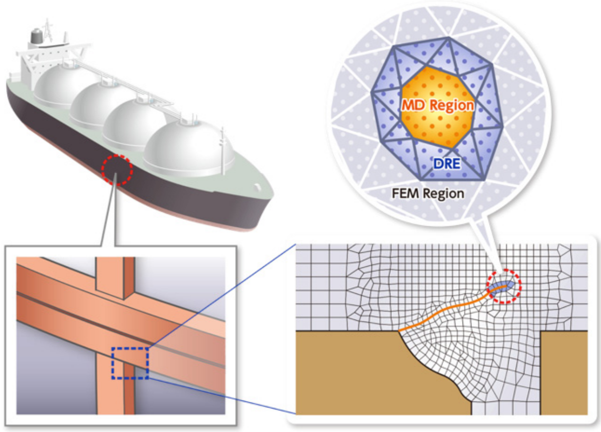

Fig. 9. Example of multiscale synthesis.

to run at an actually achievable computational load while retaining the accuracy of the model.

Levels from mesoscopic to macroscopic also have the same structure. Since macroscopic-level modelling involves integrating the behavior of individual materials, the accuracy of the overall behavior is highly dependent on the modelling accuracy of the individual structural behavior. It is necessary that the mesoscopic-level findings are properly reflected in the modelling of individual structure while balancing computational load and accuracy. Conversely, if a part is discovered that requires detailed study from results of macroscopic-level modelling, a detailed study at the mesoscopic- and microscopic-levels will be necessary. The interaction with the user and the environment at the use phase needs to be set up appropriately as boundary conditions and external forces in the macroscopic model. In addition, the results of the calculations of reactions and deformations to these external factors must be provided for consideration of comfort and safety during the use phase. This linkage to the mesoscopic level and use phase is crucial in assessing the macroscopic function of the artifacts as a framework.

A coarse-grained mesoscopic model is used on the basis of the microscopic model, and a coarse-grained macroscopic model is used on the basis of the mesoscopic model. Namely, models at three different levels, i.e., microscopic, mesoscopic, and macroscopic levels, are coupled for the simulations. By using the simulations, it is possible to form twins with a realistic computational load while maintaining high accuracy for elements directly related to improving the safety and ensuring the reliability of artifacts (**Fig. 9**).

Moreover, the most distinctive feature of the proposed DTAS is that the structure of the socio-economic system, which incorporates action entities such as related stakeholders in the use phase of artifacts, is also modeled in cyberspace. This allows us to consider the issue of risk arising from the use of artifacts. One can expect realization of an artifact system which can consider sustainable operation based on social structure, in which stakeholders around the artifact are taken into account.

4.2. Uncertainty Evaluation of DTAS

In DTAS, the twins are updated by reflecting the monitoring data from time to time. However, in modelling, including the environment of use, prior information and monitoring data on the distribution of model parameters are not always available in sufficient quality and quantity. Therefore, there is no guarantee that the model will be the only one determined to be consistent with the monitoring data. This means that there can be multiple solutions to the degradation conditions and future predictions suggested by the model.

In order to assess such uncertainty, it is important to have a large ensemble of models that are consistent with the monitoring data and to have a method of approximating the range and probability density of the predictions [70]. In order to generate such an ensemble of models, there are not only approaches that estimate probability densities based on the consistency with both prior knowledge and monitoring data [71, 72], but also non-Bayesian approaches such as the null-space Monte Carlo method [72], which searches the null-space of the models preferentially. These approaches have recently been intensively studied in the earth sciences [72, 73].

It is expected that DTAS will be able to contribute to risk assessment and other activities more appropriately by visualizing uncertainty through the development and use of such technologies. On the other hand, each stakeholder may have a different perception of the results obtained from the uncertainty assessment, and a scientific methodology that contributes to specific decision-making in this context is an issue for the future.

4.3. Toward Co-Creative Consensual Formation in Artifact System Creation

The purpose of DTAS is to monitor artifacts modelled at various scales from real space, use the data as input, and maintain the data as twins in cyberspace as artifact systems, including social systems. Furthermore, information in cyberspace can be shared widely among stakeholders to engender a new way of creating artifact systems.

In this paper, we have proposed a DTAS focusing on structural materials, but in the future, it is expected that DTAS will also be applied to artifacts other than huge artifacts, and will be retained as twins in cyberspace by reflecting and accumulating, as needed, information on the design of artifacts, information on the production process, information related to transactions in the market, and information on disposal and recycling after use. Furthermore, in response to various relevant technological advances, and with the development of the humanities and social sciences and the integration of engineering disciplines with the humanities and social sciences, the current four levels may be further subdivided into multiple levels. This would allow for the co-creation of new artifact systems through widespread sharing among stakeholders [74]. For example, a new artifact form could be proposed from the user's point of view, based on usage and adopted by the designer. Moreover, discussions among stakeholders about the social impacts of artifacts (e.g., environmental impacts) could lead to more desirable and agreed-upon new artifact systems being proposed. This could lead to a vibrant economy and society where individual consumer creativity is respected in the process of artifact creation. In addition, it will lead to the creation of a society in which security and safety are integrated, in which consumers are aware of not only the benefits but also the risks throughout the lifecycle of artifacts, and in which society as a whole can form a consensus.

By proposing new values, utilizing and verifying them, and accumulating data and technology through virtual simulations within DTAS, it will be possible to contribute to sustainable social change and development. The DTAS is not intended to target only specific artifacts in fragmented engineering fields, but is broadly applicable to the artifact systems that exist today, and it is expected that this will enhance the artifact systems.

5. Conclusions

This study proposed the concept of DTAS as a digital twin that extends the traditional digital twin concept to encompass an artifact system that includes stakeholders. In this paper, we have summarized the technologies and requirements for constructing a DTAS with a focus on structural materials. A unique feature of DTAS is that it stores models in cyberspace of levels of phenomena ranging from the atomic scale to social systems. In addition, we introduced the specific elemental technologies that the authors have developed to date and discussed the usefulness of DTAS. DTAS is still concept, and a discussion of the technical structure for its implementation. New issues may arise during the phase of integration of individual technologies and implementation of DTAS. Further research and development is expected in the future.

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Main Works:

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- "Manufacturer's strategy in a sharing economy," CIRP Annals – Manufacturing Technology, Vol.66, No.1, pp. 409-412, 2017.

Membership in Academic Societies:

- Japanese Society for Artificial Intelligence (JSAI)
- Institute of Systems, Control and Information Engineers (ISCIE)
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- "Analytical solution for a radial advection-dispersion equation including both mechanical dispersion and molecular diffusion for a steady-state flow field in a horizontal aquifer caused by a constant rate injection from a well," Hydrological Research Letters, Vol.12, No.3, pp. 23-27, 2018.
- "Land subsidence modelling for decision making on groundwater abstraction under emergency situation," Proc. IAHS, Vol.382 pp. 403-408, 2020.

Membership in Academic Societies:

- Japanese Association of Groundwater Hydrology (JAGH)
- Japan Society of Engineering Geology (JSEG)
- American Geophysical Union (AGU)
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