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Probabilistic Representation and Its Application of Digital-Twin of Spatio-Temporal Real-World Toward Trustable Cyber-Physical Interactions

Hideyuki Shimonishi , Daichi Kominami , Yuichi Ohsita , Hiroshi Yoshida , Kousuke Nogami , Dai Kanetomo , and Masayuki Murata 

ABSTRACT

The digital twin is a high-precision, real-time representation of the real world. It has evolved from a digital copy of physical objects, such as jet engines, robots, or any machine, to a broader concept to represent a space, room, building, and city, where many objects and humans interact to engage in productive activities. The digital twin has been attracting attention as an important component of cyber-physical systems in many real-world use cases where safety and trustability are critical. In this article, we argue that risk management is dramatically improved through probabilistic representation of the real world whose true status is only inferred with certain uncertainties. We introduce an evolution of the digital twin and then present a probabilistic digital twin of the real world in which the identity and status of any object are represented in a probabilistic graphical structure. Then, we introduce use cases of the probabilistic digital twin, such as probabilistic object recognition, prediction of the existence of obstacles, and risk-sensitive robot control for robotized automation in various environments such as warehouse operations.

INTRODUCTION

The Digital Twin [1], [2], [3], [4] has been proposed as a high-precision real-time representation of physical objects such as jet engines, airplanes, cars, robots, or any object whose existence and status are digitized and connected. Toward the next era, or the era of the so-called Beyond 5G/6G, connected society will develop further, and any physical object is expected to be digitized to form cyber-physical systems to solve social problems in terms of industrial robotics, healthcare, autonomous driving, etc. Therefore, the digital twin is expected to be a holistic representation of an entire space that accommodates everything that exists in that space.

As in many pieces of literature, Artificial Intelligence (AI), Machine Learning (ML), and Beyond 5G/6G technologies have empowered us to obtain more accurate and realistic digital twins. However, image recognition with cutting-edge AI algorithms is not 100% accurate; movements of motors and gears are uncertain to some extent when controlling robots, and network latency or

bandwidth, especially in wireless links, are unstable so the future status is difficult to predict. Thus, cyber-physical systems relying on uncertain information could lead to dangerous situations.

There are various classes of cyber-physical systems and computer networks that can potentially reap the benefits of advanced digital twin and AI/ML technologies [1], [10]. Among them, systems where safety is critical, for example, when many humans and robots collaborate in a shared space, or where status monitoring is unstable, for example, in high-frequency radio communication or vision-based people tracking, rely highly on cutting-edge AI/ML technologies to improve the accuracy and hence reliability of high-precision digital twins. However, improving accuracy requires large-scale neural network models and large chunks of training data, which would add to the growing use of massive GPUs, exhaustive data transfer in wide areas, and consumption of huge amounts of electrical power, which may offset improvements in accuracy and certainty. These classes of cyber-physical systems are the main target of this article.

The trustability of a cyber-physical system is so crucial that our main challenge is to cope with uncertainties. In this article, we argue that risk management is possible through probabilistic representation of the real world, as well as probabilistic prediction and probabilistic control based on this probabilistic representation, as in the case of the robot control introduced in the use cases of this paper. A digital twin probabilistically infers the real world from uncertain observations, non-deterministically predicts the future, and navigates humans, actuates robots, and controls things while considering uncertainties and avoiding risks.

In this article, we introduce the probabilistic representation of the digital twin, which we call the probabilistic digital twin. Any status of the objects in our real spaces (possibly virtual spaces as well), such as location, class label, or identity, is inferred statistically with probability distributions and stored in a digital twin. Furthermore, to realize trustable cyber-physical interactions, the probabilistic digital twin introduces a probabilistic graphical structure to represent spatial relations, temporal relations, and causal dependencies of the objects that interact with each other in the space. On the basis of this, the probabilistic

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digital twin statistically understands the situation and enables robust decision-making that takes into account diverse possibilities of current and future situations.

Probabilistic inference and/or control of cyber-physical systems have been proposed in several articles, as introduced in the section “[Evolution of Digital Twin](#)” and our own previous studies. Although these studies strongly suggest the need for a probabilistic digital twin, they only add a probabilistic component to an individual use case and have yet to propose a generalized modeling. We believe that the probabilistic digital twin is a general idea that enhances many use cases of real-world digital twins, and thus the main argument of this article is to discuss such generalized modeling and its use cases. We propose a general model in the section “[Probabilistic Representation of Digital Twin](#).” The general model also enables a digital twin platform on which various applications coexist and interoperate to shape a future open ecosystem.

We then introduce several use cases of the proposed probabilistic digital twin in the section “[Use Cases](#).” The first use case is object recognition. Our recognition method outputs what the observed object is from the information acquired by a camera and other sensors using Bayesian inference. The digital twin can be used as prior information of the recognition. We also apply the probabilistic digital twin to the prediction of moving obstacles from the results of object recognition. In this application, we construct a model of a space that contains moving obstacles. Then, we update the model each time and obtain probabilities of the existence of obstacles each time new recognition results are obtained. Then, we present a risk-sensitive robot control based on prediction using the probabilistic digital twin. The twin enables accurate assessment of risks to safety and efficiency due to stochastic disturbances in robot control by predicting probabilistic distributions of future states of robots and an environment. By sensitively avoiding risks, we can adapt our robots to complicated workplace environments.

We discuss open research questions surrounding the probabilistic digital twin in the section “[Open Research Questions](#).” And finally, we conclude our paper in the section “[Conclusion](#).”

EVOLUTION OF DIGITAL TWIN

A survey paper on digital twins [1], examines the research of digital twins in multiple application / services. The digital twin reproduces real-space situations in virtual space, simulates all kinds of situation, and predicts the future to appropriately control products, processes, services, and systems in real space, thus contributing to optimization, such as improved efficiency and ensuring safety through prevention. In this study, the definition of a digital twin first distinguishes between simulation and a digital twin in terms of seamless connection to the real world and real-time data exchange. It is important to note that simulation takes place entirely in virtual space, whereas a digital twin must be connected to the real world. Therefore, a digital twin has three elements: a real space containing physical objects, a virtual space containing virtual objects, and a bidirectional information flow connecting the real and virtual spaces, and the virtual and real spaces. The definition of the digital twin

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then states that the virtual space should change in sync with the real space and that actions in the real space should be realized in the virtual space on the basis of analysis and prediction by AI. There should also be a well-designed and accessible interface that allows for the effective use of various applications through the digital twin. At the same time, we also insist on the need to consider security and privacy so as not to damage the physical environment in which the digital twin is involved.

Another survey paper [2] discusses the historical process behind creating the concept of the digital twin and highlights the advantages of the digital twin compared with existing technologies. It also provides an overview of specific implementations of digital twin application modeling, simulation, and other platforms. The authors of the paper point out that these platforms focus on one or a few specific dimensions, making interaction, integration, and compatibility difficult. To realize future multidisciplinary applications of the digital twin, it will be necessary to achieve bidirectional communication and closed-loop control between physical entities, virtual model, and services. This is the basis for the interaction and integration of virtual and real digital twins. Our proposed probabilistic digital twin will focus on this interaction.

The proposal in [3] outlines the challenges to creating a digital twin and points out the need to be able to express uncertainty. The digital twin usually includes models of how a system will function, most of which are deterministic. However, they are difficult to represent deterministically because of both variability in system behavior and imperfect knowledge of the system. Moreover, there are enormous computational costs associated with running simulations on a digital twin. For safety, it may be more important to be able to simulate a wide range of scenarios than to be able to simulate a specific scenario with high accuracy. In this case, a fast model with some accuracy is preferred over a detailed but time-consuming model. These simulation results include uncertainty, which should be expressed in digital twins.

A more general approach to modeling uncertain relationships between uncertain variables and events involves the adoption of probabilistic graphical models. In particular, Bayesian networks, a kind of probabilistic graphical model, are often used in risk analysis to relate the states of different variables by means of conditional probability distributions and allow for consistent inferences on relevant variables by combining prior knowledge with newly acquired knowledge. Bayesian networks are also a mechanism that allows Bayesian updating of probability distributions when new knowledge becomes available, appropriately representing uncertainty.

Kapteyn et al. proposed a probabilistic graphical model to model for modeling a digital twin and its associated physical asset [4]. In this model, they handled an asset-twin system as a set of coupled dynamic systems that interact via observed data and control inputs. They modeled the system as a

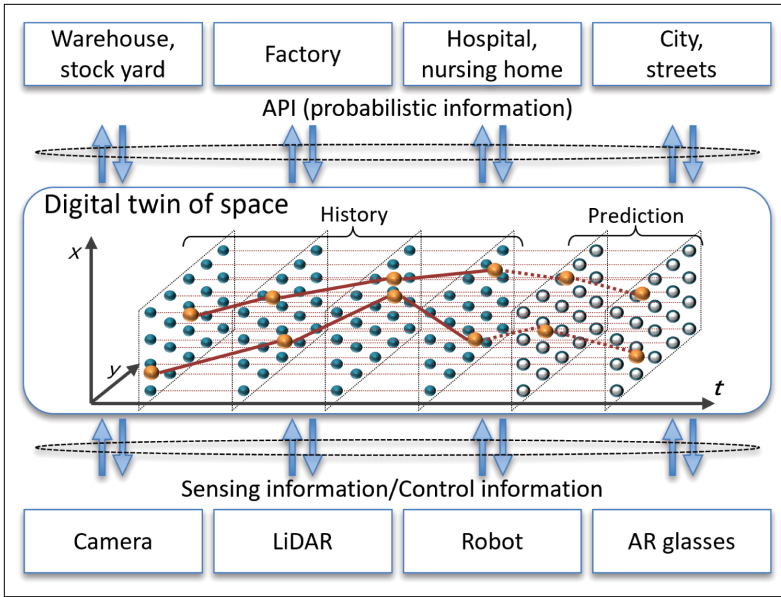


FIGURE 1. Overview of probabilistic digital twin model.

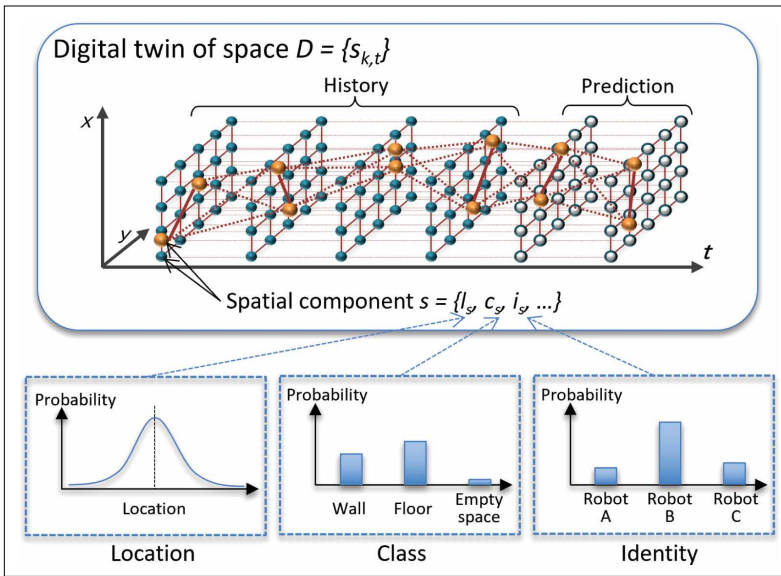


FIGURE 2. Digital twin representation of space.

probabilistic graphical model. One advantage of using probabilistic graphical models is that they are a suitable mathematical framework for representing coupled dynamic systems and can address issues such as uncertainty and missing data. Although they introduced a probabilistic model, they focused on a system that can be modeled using the theory of statistics, dynamical systems, and control theory. In comparison, this article focuses on the digital twin of space, which is composed of various components. The modeling space is the mathematical representation of spatial features such as the location and shape of physical objects.

PROBABILISTIC REPRESENTATION OF DIGITAL TWIN

MODEL OVERVIEW

Figure 1 shows an overview of the digital twin modeling. In the center of the figure, a digital twin

of the spatio-temporal structure of the real world is depicted.

We propose that the spatio-temporal components of the space can be either points in the space, shown as the blue dots in Fig. 1, forming a regular 3D grid or selected from points of interest, or they can be objects existing in the space, which are shown as orange dots in the figure. A point may represent an occupant at that point, which could be a wall, a floor, or an empty space, and the object may be a robot, human, package, etc. that may have a specific shape, be moving, or be controlled/navigated by digital twin applications.

As shown at the bottom of the figure, the digital twin is constructed and updated in real time from various sensors like cameras, LiDARs, or environmental monitors. The digital twin is also used to control objects like robots or navigate humans via AR glasses or haptic devices. At the top, applications that use the digital twin to monitor and control the real world are connected.

DIGITAL TWIN REPRESENTATION OF SPACE

A digital twin of a space D is composed of spatio-temporal components $\{s_{1,t}, s_{2,t}, \dots, s_{k,t}, \dots, s_{N,t}\}$, which are any of the points in the space-time continuum as shown in Fig. 2, and k and t are unique numbers that identify different points and time, respectively. In the model, k is used to differentiate components at a specific time and is not used to guarantee the identity of components in the time continuum; in other words, $s_{k,t}$ cannot be guaranteed to be identical to $s_{k,t-1}$. Namely, if the component is an object recognized from video images of a camera, object tracking algorithms cannot guarantee the identity of $s_{k,t}$ and $s_{k,t-1}$, but would give probabilistic inference results. Time t can be current, past, and future, assuming that a built-in (or external) prediction algorithm is used to predict the future status.

Each component $s \in D$ has its properties $\{l_s, c_s, i_s, \dots\}$, where l , c , and i are the location, class, and identity of the component, which are described below. There may be other properties such as size, weight, temperature, etc. which would be defined by the particular application, but we will not discuss further details in this article.

In this article, we argue that the digital twin representation should be probabilistic, as shown in the bottom left of Fig. 2. The location property l_s is a probability distribution. The existence of an object would be recognized from video images of a camera, and thus, its estimated location would contain a certain error due to monitoring noise or incomplete estimation algorithms. Therefore, we assumed that a location estimation algorithm would output the mean and covariance in a three-dimensional Gaussian distribution. A robot path planning algorithm can be more robust if it uses variance to calculate the safety margin.

The class property c_s is also defined as a probability distribution, as shown in the middle of the bottom of Fig. 2. When a camera captures an object and an AI/ML algorithm outputs inference results, a vector of probabilities to various labels such as a wall, floor, people, robot, empty space, etc. is stored as a digital twin, rather than

selecting the most probable inference result. In this case, for example, if a robot needs to go a longer distance from a human than other things, it could be safer if the robot considers multiple possibilities in terms of what it is facing. This differentiated risk management with a probabilistic digital twin could make robots safer and more efficient than in the case of a deterministic digital twin that faces unseen risks and acts more conservatively.

The identity property i_s is defined in a probabilistic way in both space and time continuous, as shown in the bottom right of Fig. 2. In a space where multiple (similar) objects coexist and their situations are recognized by many individual sensors, uniquely identifying them without any ambiguity is quite difficult, and thus their identity should be represented probabilistically to quantify the possibilities of scrambling. For example, if there are multiple cameras in a space, it would also be difficult to determine whether the objects taken by these cameras are identical or different. Also, in time-continuous, it would be hard to determine the identity of the objects at a specific time and a subsequent time.

PROBABILISTIC IDENTITY MODEL AND SPATIO-TEMPORAL INFERENCE

As discussed in the previous subsection, we have introduced the idea of probabilistic identity in which none of the objects in a spatio-temporal structure have an absolute identity but rather their identities are relative and probabilistic. This is our unique contribution, which enables digital twin applications to obtain multiple possible understandings of space from a digital twin platform.

Let us assume that the probabilistic digital twin is represented by a probabilistic graphical structure, which models spatio-temporal relations and causal dependencies among any component in a space. We also assume that the identity of a component is only determined by its direct adjacent components in the graph, which means that the graph has a local Markov property and is a Markov Random Field (MRF). Using the MRF as a generative model and sensor inputs as observations, we can infer the spatio-temporal structure of the space. Formal modeling of the graph and inference will be given in our future papers, but initial examples are shown below, where object recognition in the section “Object Recognition” uses Bayesian inference, and obstacle prediction in the section “Predicting Existence of Obstacles” uses Conditional Random Field (CRF) for inference.

SIGNALING AND COMPUTATIONAL COSTS FOR PROBABILISTIC DIGITAL TWIN PLATFORM

The probabilistic digital twin could impose additional signaling and computational costs to collect probabilistic data. One aspect is that digital twin instances have probabilistic representations; therefore, an additional signaling cost is required to send, receive, and store the probabilistic data. Its overhead depends on the use case, but generally, the overhead is marginal if the probability distribution follows a well-known shape like a Gaussian, representing location or

The digital twin is also used to control objects like robots or navigate humans via AR glasses or haptic devices.

temperature, and the data would be simply represented by its mean and variance. On the other hand, if a class of an object can be represented by a vector of certainties, or a relationship among objects may be represented by a graph like MRF, then the overhead becomes larger to manage these data structures.

The other aspect is related to the spatio-temporal inference described above. When an application requires information on a digital twin instance specifying its identity, the platform needs to identify any components related to that identity by solving the graphical structure introduced above. If multiple components are related to that identity, the platform needs to calculate the most plausible information by probabilistically integrating the information of the related components. The processing cost heavily depends on the size and structure of the graph structure and thus varies according to the specific use case. In this article, we provide specific numbers we have obtained via our prototype implementations.

USE CASES

In this section, we will describe some use cases of the above-mentioned digital twin model. First, multimodal object recognition using Bayesian inference is introduced to probabilistically recognize and track objects in the space, which are represented as orange dots in Figs. 1 and 2. Then, spatio-temporal inference using CRF is introduced to predict obstacle existence, which are represented as blue and white dots in those figures. Lastly, risk-sensitive robot control is introduced, where probabilistic digital twin representation is used for safe and robust robot operations.

OBJECT RECOGNITION

We previously proposed a method that mimics the recognition performed by the human brain to update a digital twin [6]. The method extracts image and location features from objects detected by an existing object detection method and outputs a probability density that represents what the detected object is based on the features. The human brain uses sensory signals obtained from the five senses to make a decision about what it has observed referring to its own memory. This multimodal recognition is known to be probabilistic and hierarchical in the brain, is lightweight and makes valid judgments based on past memories. We believe that an important solution to the probabilistic representation of the digital twin is to mimic the cognitive processes performed by the human brain.

First, we developed a unimodal object recognition method that recognizes what the observed object is on the basis of a single sensory signal (information observed from a single sensor). We also developed a method that integrates the results of unimodal object recognition with those of multiple sensors. Both methods are based on a model of the recognition process of the human brain, and, as mentioned above, we

have shown that they are relatively lightweight in terms of computation and achieve high recognition accuracy.

The Bayesian attractor model [7] models the decision-making process of the human brain. When a person observes visual information, the model outputs which of the previously presented alternatives the person has observed, along with the confidence level. In this model, a decision is made when the confidence level exceeds a certain value. The Bayesian attractor model allows us to represent the trade-off between reaction time and accuracy before a person makes a decision on observed information. By extending this model, we constructed a unimodal object recognition method that probabilistically outputs what the observed object is from the information observed by a single sensor. The computational complexity of our method is mainly decided by that of the Unscented Kalman filter [7]. It is proportional to the cube of the dimensionality of the feature.

We proposed a multimodal integration method based on a Bayesian causal inference model to integrate unimodal recognition results. In the human brain, activities in different regions of the brain are observed when visual and auditory sensory stimuli are received. This is because recognition based on visual information and recognition based on auditory information are performed in separate brain regions. Later, activity is observed in a quite different region, and it has been confirmed that the results of each type of recognition are integrated at this time. Then, causal inference is conducted for weighting during integration. Generative models for causal inference can be constructed from the digital twin. We have extended the integration method

performed in the brain and proposed a method for integrating three or more modalities using the confidence level of unimodal recognition results. Since a modality with a higher confidence level has a higher weight during integration, the more information is obtained from multiple reliable modalities, the better the recognition accuracy can be expected to be.

In our previous experiments, we extracted 128 dimensional image features from 640×480 resolution video. A depth camera was used to extract 3D location features. We have shown that our multimodal integration method is capable of real-time recognition even for 60 fps video [6].

PREDICTING EXISTENCE OF OBSTACLES

We have applied the digital twin of a space to the prediction of moving obstacles [5].

In this application, we model an area that contains obstacles using the CRF. Figure 3 shows the model. In this model, we divide the area into sub-areas and introduce a component to each sub-area and each time slot. Each component is shown as a vertex in Fig. 3. Each component has a property indicating the state defined by the existence of obstacles and the class property of the obstacles in the corresponding sub-area and time slot.

The components have spatial and temporal correlations. For example, if an obstacle exists in a certain sub-area, the obstacle may exist in the adjacent sub-area to where the obstacle may move in the next time slot. In Fig. 3, edges are added between the components with correlations, and the joint probabilities for the states of the components are defined.

We also add monitored information to this model. We can use the results of the object recognition explained in the section “Object

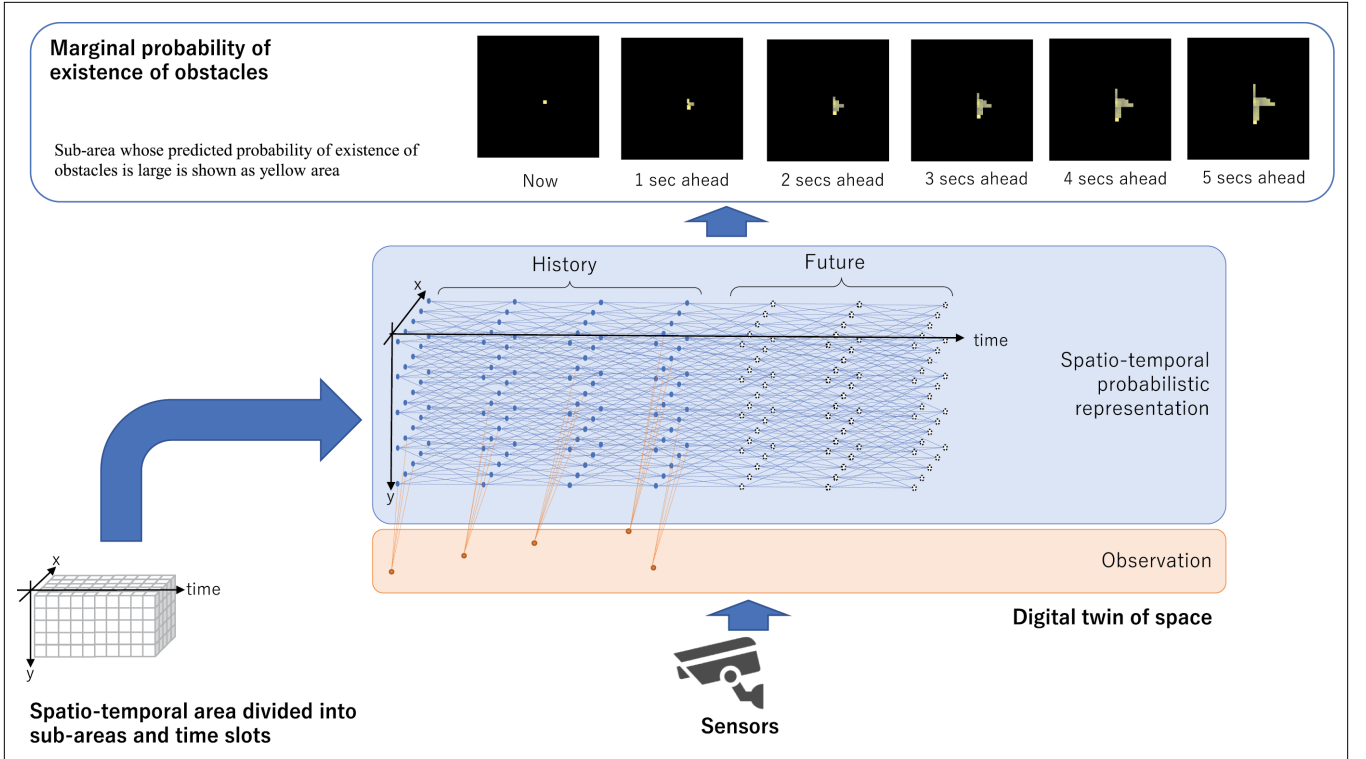


FIGURE 3. Prediction of obstacle existence based on digital twin of space.

Recognition” as the monitored information. We add the components corresponding to the monitored information and define the correlation between the components corresponding to the monitored information and the components of the state of the related sub-areas.

We can predict the existence of obstacles by updating the model each time new observations are obtained. By using the updated model, we can obtain the probability of the existence of obstacles in each sub-area by calculating the marginal probability for the sub-area. As this model is based on the CRF, the marginal probabilities can be calculated by using the loopy belief propagation algorithm. By obtaining the marginal probabilities of the random variables corresponding to future time slots, we can predict the probabilities of the existence of moving obstacles, which can be used by the robot control considering risk (see the section “**Risk-Sensitive Robot Control**”).

The model for obstacle prediction can be maintained on a computer other than that maintaining a full digital twin. In this case, we can update the model by obtaining information on new observations, including the locations, IDs, and uncertainty of the detected obstacles from the computer maintaining the digital twin. The amount of this information is only a few tens of bytes per obstacle.

After updating the model, the computer calculates the marginal probabilities without any interaction with other computers. The calculation time for the marginal probabilities is $O(NEL^2)$, where N is the number of components, E is the number of edges, and L is the number of labels in the model. By focusing only on small areas that may contain obstacles, we can reduce N and E . We demonstrated that our method could update the model and calculate the marginal probabilities for five time slots within 100 ms by using a program implemented using C++ and one core of a 3.06-GHz Intel Xeon E-8867 processor [11]. This calculation time is sufficiently small enough to be used for robot control in a warehouse where only people and transport robots move because no obstacle moves more than a few tens of centimeters in 100 ms.

RISK-SENSITIVE ROBOT CONTROL

Various industries, including logistics, manufacturing, and construction, have considered the automation of work with robots to solve labor shortages and ensure worker safety. However, robotization has progressed in only a tiny portion of all industries. This is mainly because many on-site operations are subject to stochastic disturbances that are not known in advance. Stochastic disturbances undermine the safety and efficiency of robot automation and are a barrier to their introduction.

Stochastic disturbances can be divided into those caused by the robot and its environment. Robotic stochastic disturbances include robot modeling errors, errors in internal sensors, individual differences, aging, and mechanical backlash. On the environmental side, they include the condition of the road surface, the movement of the operator (a dynamic obstacle), and errors in the external sensors.

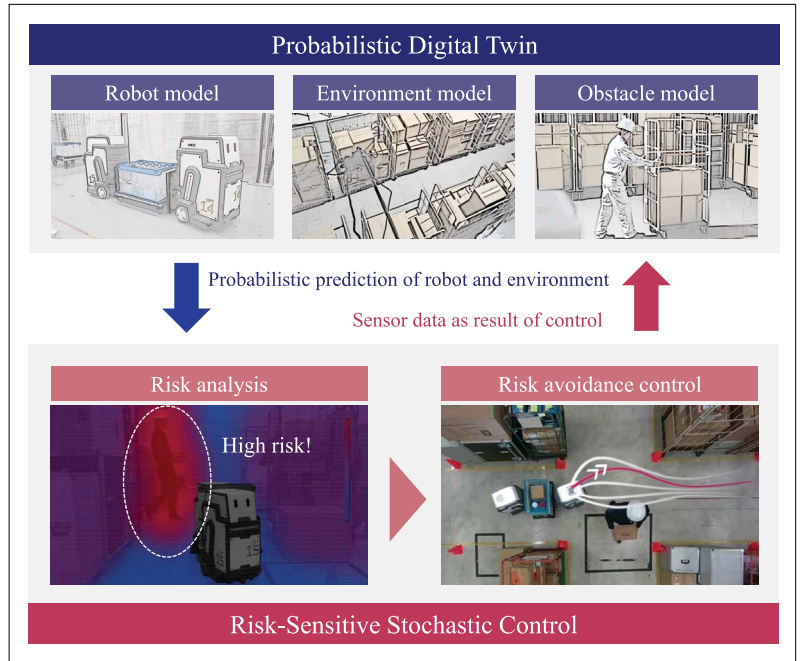


FIGURE 4. Probabilistic digital twin and risk-sensitive stochastic control for transport robots in warehouse. Probabilistic digital twin has probabilistic model of transport robots, environment, and obstacles and inputs future predictions based on these probabilistic models to risk-sensitive stochastic control. Risk-sensitive stochastic control analyzes safety and efficiency risks from received future predictions and takes risk-averse actions. Probabilistic digital twin acquires results of these actions using sensors and reflects them in updating probabilistic models and in next future prediction.

The strength of the probabilistic digital twin is that it represents the robot and its environment in a form that explicitly includes stochastic disturbances and can predict the future. In this subsection, we present a method for utilizing the probabilistic digital twin and risk-sensitive stochastic control [8], [9] in robot control to avoid safety and efficiency risks and eliminate robot malfunctions caused by stochastic disturbances. Figure 4 illustrates the functional configuration of the probabilistic digital twin and risk-sensitive stochastic control, using a transport robot in a warehouse as an example.

Originally used in mathematical finance, risk-sensitive stochastic control is a technique for building portfolios that generate as much profit as possible while avoiding the risk of asset fluctuations. We applied this technique to robot control to pursue efficiency as much as possible while avoiding safety risks. In risk-sensitive stochastic control, the stochastic differential equation $dx_t = f(x_t, u_t)dt + \sigma(x_t, u_t)dB_t$ represents robot dynamics explicitly including stochastic disturbances. x_t is the robot state variable, u_t is the control input, $f(x_t, u_t)$ is the deterministic dynamics, and $\sigma(x_t, u_t)dB_t$ is the stochastic variation term driven by Brownian motion.

We construct the stochastic differential equation model of the robot and the obstacle existence probability model (see the section “**Predicting Existence of Obstacles**”) in the probabilistic digital twin. By predicting the probability distribution of the robot and obstacles in the future when a specific control input is applied to the robot in the digital twin, a risk-sensitive evaluation function

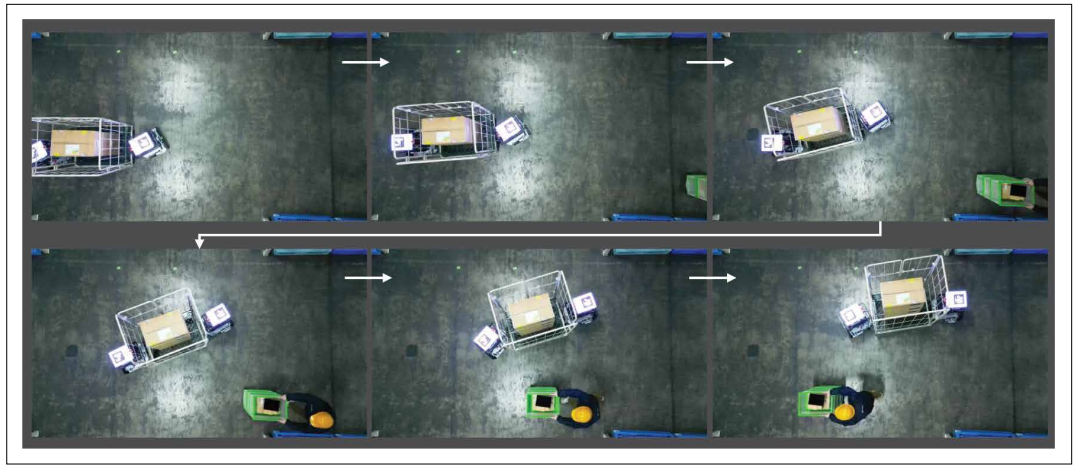


FIGURE 5. Experiment with transport robot control based on risk-sensitive stochastic control. This figure shows behavior of cooperative transport robots in avoiding collision risk with worker walking in front of them. Robots follow travel path that is sure to avoid collisions as well as decreases in efficiency on basis of predictions of control errors of robots and worker's movement.

The digital twin has been expected as realistic solutions for social problems in many real-world use cases, including manufacturing, warehouse operations, smart city, area monitoring, nursing homes, etc., where safety and trustability are critical.

$J = \beta^{-1} \ln \mathbb{E}[\exp(\beta S)]$ for safety and efficiency is calculated as the following equation. S is the normal evaluation function and β is a risk parameter. The larger β is, the more sensitive to risk the evaluation function can be set.

We compute the risk-sensitive evaluation functions for multiple pre-sampled candidates of control input to the robot by referring to the probabilistic digital twin's future prediction. The control input that minimizes the risk-sensitive functions is selected as the input to the robot.

When the control period is Δt , the predicted horizon is h , the number of candidate control inputs is n , and the number of iterations for computing the probability distribution is m , the computational cost of this risk-sensitive robot control is expressed as $\mathcal{O}\left(\frac{h}{\Delta t} nm\right)$. Although the proposed method requires m times the computational cost compared with general predictive control (e.g., Model Predictive Control), we have achieved real-time computation at over 15 Hz (under 60 ms/period) on a computer with a Core i7-11700 [9].

Figure 5 shows an experiment in which risk-sensitive robot control was applied to cooperative transport robots (the two robots sandwiched the cart between them to transport it). The robots avoided the risk of colliding with a worker walking from the front, ensuring safety and preventing a loss of efficiency by not stopping in the middle of the transportation task. We also showed that the probabilistic digital twin could avoid safety risks when the robots transferred on a cluttered narrow path in [8]. Specifically, while the conventional deterministic optimal control collided with obstacles 5 out of 15 times, the risk-sensitive stochastic control

could reduce the number of collisions to zero while maintaining the same level of speed as the optimal control.

OPEN RESEARCH QUESTIONS

Inspired from the information processing mechanism of the brain, we constructed a method for probabilistic object recognition. This method models information accumulation and decision making using Bayesian inference, and we believe that extending the model can bring about the updating of already acquired knowledge and the acquisition of new knowledge. This approach is expected to lead to the realization of tasks for recognizing objects in environments where no prior information exists.

More accurate obstacle prediction would achieve a higher application efficiency using the prediction results. To predict obstacles more accurately, we need to construct more sophisticated models of obstacle movements. Sophisticated models may require more detailed information on obstacles. Methods are also needed to obtain detailed information.

Risk-sensitive robot control is based on probabilistic models of the robot and the environment, which are identified from a large amount of data obtained through repeated experiments. To improve the practicality, techniques are needed to automatically learn these probabilistic models.

CONCLUSION

In this article, we have introduced an evolution of the digital twin for cyber-physical systems. The digital twin has been expected as realistic solutions for social problems in many real-world use cases, including manufacturing, warehouse operations, smart city, area monitoring, nursing homes, etc., where safety and trustability are critical. In this article, we propose a probabilistic representation of the digital twin of the spatial structure of the entire space to realize trustable cyber-physical systems. Any component, whether a grid point or an object, in the space is represented by its location, class, identity, or any other properties with their probability distributions. Then, we introduce some use cases of

the probabilistic digital twin. Probabilistic object recognition is based on the multimodal recognition model of the human brain, which represents the recognition results probabilistically. Our proposed method uses the Bayesian attractor model and a Bayesian causal inference model, which mimic the multimodal recognition of the human brain. The probabilistic digital twin can be used to predict the existence of moving obstacles. By probabilistically representing the space containing moving obstacles and updating the model each time new observations are obtained, we construct the timely model of the space. Based on the model, we can predict the probabilities of the existence of obstacles in future time slots. In addition to the obstacle prediction, expressing a robot's dynamics, including stochastic disturbance, with a stochastic differential equation allows us to analyze the risk of safety and efficiency in robot control. The risk-sensitive robot control can avoid the risk and allows for the social implementation of industrial robots.

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