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FORMAL SPECIFICATION OF MULSEMEDIA OBJECT'S DIGITAL TWIN BASED ON DISCRETE INTERVALS TEMPORAL RELATIONS

The article proposes a modification of the relations between discrete intervals, which makes it possible to formally determine the relationship between sets of temporal data of different modalities for the formal description of a mulsemedia object`s digital twin model. A mulsemedia object is a physical object, the state of which is recorded using a set of sensors to form a temporal multimodal digital description that comprehensively defines the object as a person perceives it through the senses. A digital twin of a mulsemedia object is a complex software model of this object, which is designed to predict the possible states and behaviour of the mulsemedia object. The formal description of a mulsemedia object is based on data obtained from a set of sensors, each of which captures information of a certain modality. To combine these data into a single object specification, a temporal relationship must be established between them, since data from different modalities can be registered and be meaningful for the research in different periods of the object`s observation. Qualitative determination of the temporal relationship between sets of data can be done using relations between discrete intervals ("Is Before", "Is After", "Coincides", etc.), but quantitative determination (for example, "How much before") using existing relations discrete intervals are impossible. Therefore, the article proposes to consider existing relations of discrete intervals as qualitative relations, at the same time, introducing their modification - quantitative relations of discrete intervals. The use of quantitative relations of discrete intervals will make it possible to simplify the development of digital twin technology software by improving the quality of the formal specification of data structures that comprehensively reflect interconnected sets of temporal multimodal data obtained in the process of monitoring mulsemedia objects.
Keywords: mulsemedia, digital twins, software, discrete intervals, relations, temporal multimodal data.

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ФОРМАЛЬНА СПЕЦИФІКАЦІЯ ЦИФРОВОГО ДВІЙНИКА МУЛЬСЕМЕДІЙНОГО ОБ'ЄКТА НА ОСНОВІ КІЛЬКІСНИХ ВІДНОШЕНЬ ДИСКРЕТНИХ ІНТЕРВАЛІВ

У статті запропоновано модифікацію відношень дискретних інтервалів, яка дає змогу формально визначати зв'язок між наборами темпоральних даних різних модальностей для формального опису моделі цифрового двійника мульсемедійного об'єкта. Під мульсимедійним об'єктом розуміється фізичний об'єкт, стан якого фіксується за допомогою набору сенсорів для формування темпорального мультимодального цифрового опису, який комплексно визначає об'єкт подібно до того, як він сприймається людиною через органи чуття. Цифровий двійник мульсемедійного об'єкта є складеною програмною моделлю цього об'єкта, яка призначена для прогнозування можливих станів та поведінки мульсемедійного об'єкта. Формальний опис мульсемедійного об'єкта відбувається на основі даних, що отримуються з набору сенсорів, кожен з яких фіксує інформацію певної модальності. Для об'єднання цих даних у єдину специфікацію об'єкта між ними потрібно встановити темпоральний зв'язок, оскільки дані різних модальностей можуть реєструватися та мати сенс для дослідження у різні періоди спостереження об'єкта. Якісне визначення темпорального зв'язку між наборами даних може бути виконане за допомогою відношень між дискретними інтервалами («передує», «настає після», «збігається» та інші), проте кількісне визначення (наприклад, «наскільки передує») за допомогою існуючих відношень дискретних інтервалів неможливе. Тому у статті запропоновано вважати наявні відношення дискретних інтервалів якісними відношеннями, натомість ввести їхню модифікацію – кількісні відношення дискретних інтервалів. Використання кількісних відношень дискретних інтервалів дасть змогу спростити розроблення програмного забезпечення технології цифрових двійників за рахунок підвищення якості формальної специфікації структур даних, які комплексно відображають взаємопов'язані набори темпоральних мультимодальних даних, що отримуються у процесі моніторингу мульсемедійних об'єктів.
Ключові слова: мульсемедіа, цифрові двійники, програмне забезпечення, дискретні інтервали, відношення, темпоральні мультимодальні дані.

Introduction

Since its development, the digital twins technology has been used to solve a wide range of scientific and technical problems. One of these tasks is the task of computer modelling of mulsemedia objects. A mulsemedia object is a physical object or a composition of several physical objects, the state of which is recorded using sensors. Each sensor captures information of a specific modality. A set of sensors produce temporal multimodal information that can be used for forming a digital description which comprehensively defines the object as people can perceive it through their senses. A digital twin of a mulsemedia object is a complex software model of this object, which is designed to predict the possible states and behaviour of the mulsemedia object. To combine these data into a single object specification, a temporal relationship between them must be defined, since data from different modalities can be registered and have a specific value for the research in different periods of the object`s observation.

The research presented in this paper is aimed at the advancement of the theoretical foundations for temporal multimodal data representation that can be used for the formal specification of the mulsemedia object's digital twin.

Related works

The fundamentals of the temporal relations were proposed in works [1] and [2] where the foundations of interval algebra and interval-based temporal logic are defined. In particular, in the paper [1] thirteen relations between intervals are proposed. In the paper [2] the beginnings and endings of intervals are formally defined and associated with points on the time axis.

In the paper [3], considers three types of relations between events: temporal relations between an event and a time expression, between a pair of events and between an event and the document creation time. It proposes a Markov Logic model that jointly identifies relations of all three relation types simultaneously. It allows to improve the accuracy while solving tasks where temporal relations between events are important.

In the paper [4], a notion of a fuzzy time interval is formulated and fuzzy Allen relations which are the generalization of Allen's interval relations are proposed. The relatedness measures are applied to define fuzzy temporal relations between vague events.

The paper [5] focuses on temporal link labelling as a classification task, in particular, it considers a set of temporal relations specified in TimeML [6] that contains fourteen types of relations. The paper presents a way of choosing the right feature vectors to build the classification model.

The analysis of these and similar papers show that neither of researches deals with the temporal relations defined quantitatively. Moreover, most of the research focus on the use of interval algebra and interval-based temporal logic which consider continuous intervals. At the same time, discrete intervals can be more useful for the development of new algorithms and software for digital twins technology.

Theoretical Background

The basis for the research presented in this paper is the Algebraic System of Aggregates (ASA) [7, 8]. The ASA is an algebraic system, a carrier of which is an arbitrary set of specific structures – aggregates. In broader sense, an aggregate can be considered as a complex data structure for a consolidated representation of temporal multimodal data sets which define the same object of observation.

Mathematically, an aggregate D is a tuple of arbitrary tuples, elements of which belong to predefined sets:

$$D = [\![M_j \mid \left\langle d_i^j \right\rangle_{i=1}^{n_j}]\!]_{j=1}^{N} = [\![\{D\} \mid \langle D \rangle]\!], \tag{1}$$

where $\{D\}$ is a tuple of sets M_j, $\langle D \rangle$ is a tuple of elements tuples $\left\langle d_i^j \right\rangle_{i=1}^{n_j}$ corresponding to the tuple of sets ($d_i^j \in M_j$).

As an algebraic system, the ASA consists of three sets: a carrier (non-empty set), a set of operations, and a set of relations. This research is focused on relations of the ASA, in particular, the relations between discrete intervals.

A discrete interval (DI) [9] is a tuple, elements of which are unique values ordered either in ascending or in descending order. In broader sense, a DI is a tuple of values defining the moments of time when characteristics of the object of observation are to be measured.

In the ASA, the following relations between two DIs are defined.

The relation *Is Before* means that the first DI ($\overline{t^1}$) finishes before the second DI ($\overline{t^2}$) starts:

$$\overline{t^1} \leftarrow \overline{t^2} \text{ if } t_{n_1}^1 < t_1^2 . \tag{2}$$

The relation *Is After* means that the first DI ($\overline{t^1}$) starts after the second DI ($\overline{t^2}$) finishes:

$$\overline{t^1} \rightarrow \overline{t^2} \text{ if } t_1^1 > t_{n_2}^2 . \tag{3}$$

The relation *Coincides With* means that two DIs ($\overline{t^1}$ and $\overline{t^2}$) start and finish at the same time:

$$\overline{t^1} \leftrightarrow \overline{t^2} \text{ if } t_1^1 = t_1^2, t_{n_1}^1 = t_{n_2}^2 \text{ and } n_1 = n_2 . \tag{4}$$

The relation *Meets* means that the first DI ($\overline{t^1}$) finishes at the same time moment as the second DI ($\overline{t^2}$) starts:

$$\overline{t^1} \mapsfrom \overline{t^2} \text{ if } t^1_{n_1} = t^2_1 . \tag{5}$$

The relation *Is Met By* means that the first DI ($\overline{t^1}$) starts at the same time moment as the second DI ($\overline{t^2}$) finishes:

$$\overline{t^1} \mapsto \overline{t^2} \text{ if } t^2_{n_2} = t^1_1 . \tag{6}$$

The relation *Overlaps* means that the second DI ($\overline{t^2}$) starts during the first DI ($\overline{t^1}$) and it finishes after the first DI finishes:

$$\overline{t^1} \hookleftarrow \overline{t^2} \text{ if } t^1_1 < t^2_1 \text{ and } t^1_{n_1} < t^2_{n_2} \text{ and } t^2_1 < t^1_{n_1} . \tag{7}$$

The relation *Is Overlapped By* means that the first DI ($\overline{t^1}$) starts during the second DI ($\overline{t^2}$) and it finishes after the second DI finishes:

$$\overline{t^1} \hookrightarrow \overline{t^2} \text{ if } t^2_1 < t^1_1 \text{ and } t^2_{n_2} < t^1_{n_1} \text{ and } t^1_1 < t^2_{n_2} . \tag{8}$$

The relation *During* means that the first DI ($\overline{t^1}$) starts after the second DI ($\overline{t^2}$) starts and it finishes before the second DI finishes:

$$\overline{t^1} \curvearrowleft \overline{t^2} \text{ if } t^1_1 > t^2_1 \text{ and } t^1_{n_1} < t^2_{n_2} . \tag{9}$$

The relation *Contains* means that the first DI ($\overline{t^1}$) starts before the second DI ($\overline{t^2}$) starts and it finishes after the second DI finishes:

$$\overline{t^1} \curvearrowright \overline{t^2} \text{ if } t^1_1 < t^2_1 \text{ and } t^1_{n_1} > t^2_{n_2} . \tag{10}$$

The relation *Starts* means that the first DI ($\overline{t^1}$) starts at the same moment of time as the second DI ($\overline{t^2}$) starts and it finishes before the second DI finishes:

$$\overline{t^1} \leftarrowtail \overline{t^2} \text{ if } t^1_1 = t^2_1 \text{ and } t^1_{n_1} < t^2_{n_2} . \tag{11}$$

The relation *Is Started By* means that the first DI ($\overline{t^1}$) starts at the same moment of time as the second DI ($\overline{t^2}$) starts and it finishes after the second DI finishes:

$$\overline{t^1} \rightarrowtail \overline{t^2} \text{ if } t^1_1 = t^2_1 \text{ and } t^1_{n_1} > t^2_{n_2} . \tag{12}$$

The relation *Finishes* means that the first DI ($\overline{t^1}$) starts after the second DI ($\overline{t^2}$) starts and it finishes at the same moment of time as the second DI finishes:

$$\overline{t^1} \looparrowleft \overline{t^2} \text{ if } t^1_1 > t^2_1 \text{ and } t^1_{n_1} = t^2_{n_2} . \tag{13}$$

The relation *Is Finished By* means that the first DI ($\overline{t^1}$) starts before the second DI ($\overline{t^2}$) starts and it finishes at the same moment of time as the second DI finishes:

$$\overline{t^1} \looparrowright \overline{t^2} \text{ if } t_1^1 < t_1^2 \text{ and } t_{n_1}^1 = t_{n_2}^2 . \quad (14)$$

All the abovementioned relations are qualitative. The further research offers the new approach that enables modifying these relations to make them quantitative.

Proposed Approach

The following quantitative relations are proposed in this research to enable defining relations between two discrete intervals by a specific number of time moments.

The relation *Is Quantitively Before* means that the DI $\overline{t^1}$ finishes τ moments of time before the DI $\overline{t^2}$ starts:

$$\overline{t^1} \underset{\tau}{\leftarrow} \overline{t^2} \text{ if } t_1^2 = t_{n_1}^1 + \tau . \quad (15)$$

The relation *Is Quantitively After* means that the DI $\overline{t^1}$ starts τ moments of time after the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{\tau}{\rightarrow} \overline{t^2} \text{ if } t_1^1 = t_{n_2}^2 + \tau . \quad (16)$$

The relation *Quantitively Overlaps* means that the DI $\overline{t^2}$ starts τ_s moments of time after the DI $\overline{t^1}$ starts and it finishes τ_f moments of time after the DI $\overline{t^1}$ finishes:

$$\overline{t^1} \underset{(\tau_s,\tau_f)}{\hookleftarrow} \overline{t^2} \quad \text{if} \quad t_1^2 = t_1^1 + \tau_s \text{ and } t_{n_2}^2 = t_{n_1}^1 + \tau_f . \quad (17)$$

The relation *Is Quantitively Overlapped By* means that the DI $\overline{t^1}$ starts τ_s moments of time after the DI $\overline{t^2}$ starts and it finishes τ_f moments of time after the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau_s,\tau_f)}{\hookrightarrow} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 + \tau_s \text{ and } t_{n_1}^1 = t_{n_2}^2 + \tau_f . \quad (18)$$

The relation *Quantitively During* means that the DI $\overline{t^1}$ starts τ_s moments of time after the DI $\overline{t^2}$ starts and it finishes τ_f moments of time before the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau_s,\tau_f)}{\curvearrowleft} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 + \tau_s \text{ and } t_{n_2}^2 = t_{n_1}^1 + \tau_f . \quad (19)$$

The relation *Quantitively Contains* means that the DI $\overline{t^1}$ starts τ_s moments of time before the DI $\overline{t^2}$ starts and it finishes τ_f moments of time after the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau_s,\tau_f)}{\curvearrowright} \overline{t^2} \quad \text{if} \quad t_1^2 = t_1^1 + \tau_s \text{ and } t_{n_1}^1 = t_{n_2}^2 + \tau_f . \quad (20)$$

The relation *Quantitively Starts* means that the DI $\overline{t^1}$ starts at the same moment of time as the DI $\overline{t^2}$ starts and it finishes τ moments of time before the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau)}{\leftarrowtail} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 \text{ and } t_{n_2}^2 = t_{n_1}^1 + \tau . \quad (21)$$

The relation *Is Quantitively Started By* means that the DI $\overline{t^1}$ starts at the same moment of time as the DI

$\overline{t^2}$ starts and it finishes τ moments of time after the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau)}{\rightarrowtail} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 \text{ and } t_{n_1}^1 = t_{n_2}^2 + \tau . \tag{22}$$

The relation *Quantitively Finishes* means that the DI $\overline{t^1}$ starts τ moments of time after the DI $\overline{t^2}$ starts and it finishes at the same moment of time as the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau)}{\hookleftarrow} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 + \tau \text{ and } t_{n_1}^1 = t_{n_2}^2 . \tag{23}$$

The relation *Is Quantitively Finished By* means that the DI $\overline{t^1}$ starts τ moments of time before the DI $\overline{t^2}$ starts and it finishes at the same moment of time as the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau)}{\looparrowright} \overline{t^2} \quad \text{if} \quad t_1^2 = t_1^1 + \tau \text{ and } t_{n_1}^1 = t_{n_2}^2 . \tag{24}$$

The relations *Coincides With*, *Meets*, and *Is Met By* do not have their qualitive and quantitative versions as these relations are always defined by specific moments of time and, thus, they can be considered either as qualitive or as quantitative depending on the context.

The proposed quantitative relations between discrete intervals can be useful for the formal specification of a complex data structure based on a multi-image concept [8].

A multi-image is a complex representation of temporal multimodal data sets which describe an object. In mathematical sense, the multi-image *MI* is an aggregate, the first data tuple of which is a non-empty tuple of time values.

$$MI = [\![T, M_1, \ldots, M_N | \langle t_k \rangle_{k=1}^{\tau}, \langle d_{k_1}^1 \rangle_{k_1=1}^{n_1}, \ldots, \langle d_{k_N}^1 \rangle_{k_N=1}^{\mathrm{N}}]\!], \tag{25}$$

where T is a set of time values; $\tau \geq n_i, i \in [1, \ldots, N]$.

Thus, T is a mathematical representation of the common time scale which defines the whole period of the object's observation. However, for the development of an algorithm of the object's multi-image processing, it can be useful to present in an evident way the interrelation of different data modalities in terms of time. The definition of the multi-image as the formula (25) does not provide such representation. Let us use the quantitative relations to advance the definition of the multi-image.

Firstly, let us define a sub-multi-image SMI_i which presents temporal data of i-modality as:

$$SMI_i = [\![T_i, M_i | \langle t_{k_i}^i \rangle_{k_i=1}^{\tau_i}, \langle d_{k_i}^i \rangle_{k_i=1}^{n_i}]\!], \tag{26}$$

where T_i is a set of time values which defines the time moments $\langle t_{k_i}^i \rangle_{k_i=1}^{\tau_i}$ when the data $\langle d_{k_i}^i \rangle_{k_i=1}^{n_i}$ of i-modality (the modality is defined by a set M_i) is to be measured; $i \in [1, \ldots, N]$.

Then, the multi-image *MI* can be defined as:

$$MI = SMI_{i_1} \left(R_{i_1 i_2}\right) SMI_{i_2}, \;\; i_1 \neq i_2, \;\; \forall i_1, i_2 \in [1, \ldots, N], \tag{27}$$

where $R_{i_1 i_2}$ is a quantitative relation between discrete intervals $\langle t_{k_i}^{i_1} \rangle_{k_i=1}^{\tau_{i_1}}$ and $\langle t_{k_i}^{i_2} \rangle_{k_i=1}^{\tau_{i_2}}$ of SMI_{i_1} and SMI_{i_2} accordingly.

The interpretation of the multi-image concept defined by the formula (27) enables establishing of temporal relationships between data sets of different modalities. In turn, this can allow to simplify the formal specification of a complex data structure for mulsemedia object's digital twin description.

The visualization of a formal specification based on the modified definition of a multi-image can be presented as an oriented graph. This specification is further called a *temporal specification* of a multi-image. The following example demonstrates how a temporal specification can be defined.

Let the mulsemedia object be a real nature scene where forest fire appears during the process of the forest massif observation. The observation is carried out by using the following devices: two video cameras, four audio recorders, a smell detector, and an air motion detector. Later, the data recorded using these devices are used for creating mulsemedia content (mulsemedia movie) for its reproduction in an educational immersive environment. According to the proposed approach, the mulsemedia object must be described by a temporal specification with the purpose of the creation of such a mulsemedia product – the mulsemedia movie.

Let us specify the following SMIs to be used for the mulsemedia object's specification: SMI_1 is the first video; SMI_2 is the second video; SMI_3 is the first audio; SMI_4 is the second audio; SMI_5 is the third audio; SMI_6 is the forth audio; SMI_7 is the smell record; and SMI_8 is the air motion record. Each of these SMIs has its own DI when the modality data of this SMI is obtained. The modalities timing is shown on Fig. 1.

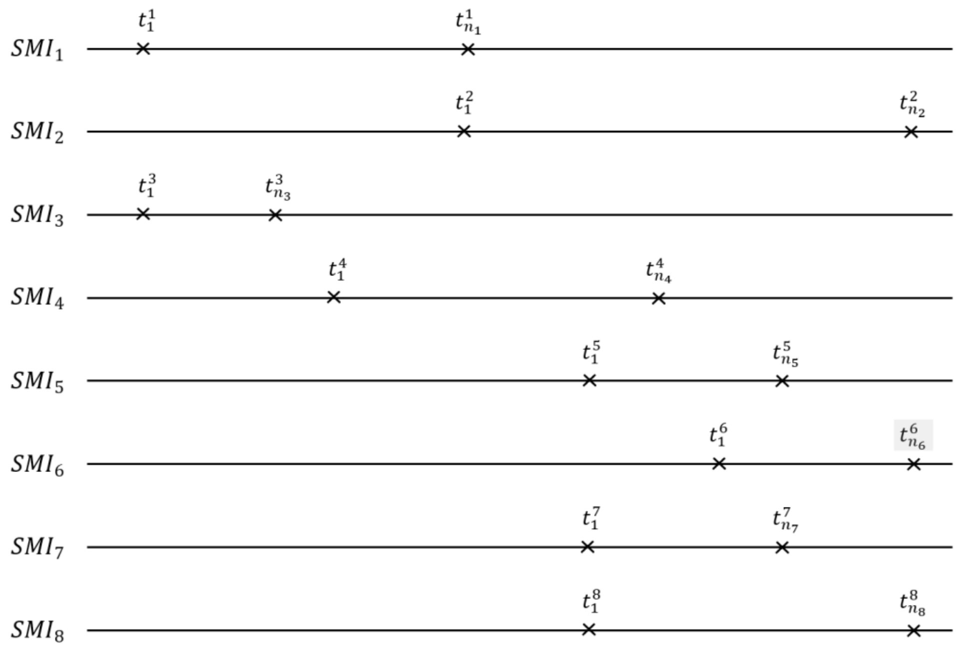

Fig. 1. The scheme of modalities timing

This scheme of modalities timing allows to calculate the following time values which are necessary for defining the qualitive relations between the DIs:

$$\begin{cases} w_1 = t_{n_1}^1 - t_{n_3}^3 \\ w_2 = t_1^4 - t_{n_3}^3 \\ w_3 = t_1^4 - t_1^1 \\ w_4 = t_{n_4}^4 - t_{n_1}^1 \\ w_5 = t_1^5 - t_1^4 \\ w_6 = t_{n_5}^5 - t_{n_4}^4 \\ w_7 = t_1^5 - t_1^2 \\ w_8 = t_{n_2}^2 - t_{n_5}^5 \\ w_9 = t_1^6 - t_1^5 \\ w_{10} = t_{n_6}^6 - t_{n_5}^5 \\ w_{11} = t_1^6 - t_1^2 \\ w_{12} = t_{n_8}^8 - t_{n_7}^7 \\ w_{13} = t_{n_8}^8 - t_{n_5}^5 \end{cases} \quad (28)$$

Then the multi-image for the given example can be defined by the temporal specification depicted on Fig. 2.

The next step is the realization of the obtained temporal specification in a program code. It can be done by using either a general-purpose programming language, or a domain-specific programming language ASAMPL 2.0 [10]. The advantage of using ASAMPL is that it is optimized for processing specifically temporal multimodal data. To support further simplification of the realization of the temporal multimodal data processing algorithms for the development of the mulsemedia software, the proposed quantitative relations need to be implemented in the syntax of the programming language ASAMPL.

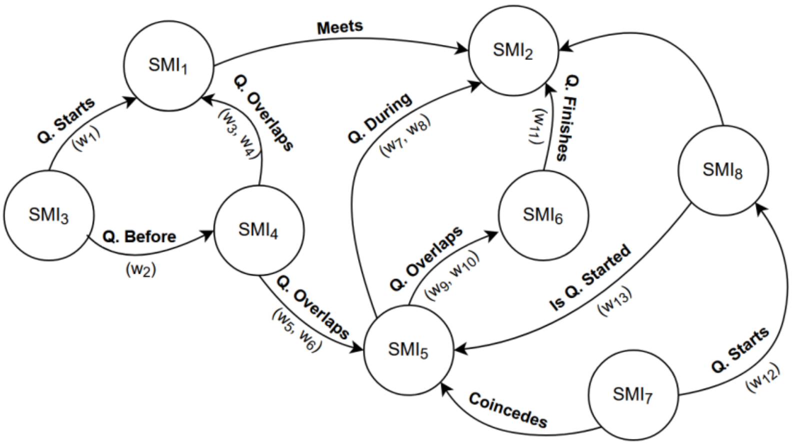

Fig. 2. The multi-image temporal specification ("Q." means "Quantitative")

Conclusions

The research presented in this article enables improving the mathematical apparatus for processing discrete intervals, which is a development of Allen's interval algebra. Unlike Allen's intervals, discrete intervals allow to determine discrete events, which in turn enables using the interval relations defined in the Algebraic System of Aggregates for the development of software for a mulsemedia object's digital twin implementation and usage.

The distinguishing feature of the new approach presented in this paper is that two types of relations between discrete intervals have been introduced; they are qualitative relations and quantitative relations. The qualitative relations are relations originally defined for discrete intervals in the Algebraic System of Aggregates. The quantitative relations are introduced in this paper for the first time. These relations enable defining how close or far the beginning and ending points of two discrete intervals are on the time axis. This allows to simplify the formal specification of the complex data structure for a mulsemedia object's digital twin representation based on temporal multimodal data to be received from a set of sensors which monitor the mulsemedia object.

Further research can be focused on the development of new advanced algorithms for temporal multimodal data processing as well as it must include the implementation of the quantitative relations in the syntax of the programming language ASAMPL 2.0.

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