Event Representation for Sensor Data Grounding

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Summary
The event representation together with the sensor data grounding method, both presented here, relates sensor reading values to natural language (NL) phrase descriptions. The representation consists of (1) event descriptors each of which has its own physical quantity expression that reflects an interpretation of an event and (2) a composition rules. As an application of the event representation, the event search system is briefly described.

Key words: *event representation, sensor data grounding, sensor network*

1. Introduction

In applications based on sensor networks which monitor the physical world and detect events occurring in the world, events are named according to attributes that have scalar values or ranges of scalar values, such as temperature and light levels. These events, which are described by SQL-like languages (TinyDB [1], Cougar [2], Xue & Luo [3]), depend on the value of a particular sensor reading.

The event descriptions given by these languages enable applications to provide services that are activated by the occurrence of certain events. The languages, however, describe only events that can be represented using values from sensor readings. Thus, humans can neither naturally represent an event using the languages nor intuitively capture the event represented by the descriptions.

This article presents an event representation together with a method that grounds sensor data. The event representation is a middle language between sensor reading values and NL–phrase descriptions.

2. Event Representation

As a middle language between event description using natural language and the values of the sensor readings, we design a representation consisting of a set of NL words and rules. We set the following three requirements for designing the representation:

Compatibility. The representation description is easily translated into an NL word or an NL phrase.

Descriptive power. The representation covers as many events described by NL sentences as possible.

Observability. The occurrence of an event described by the representation is determined by a physically observable phenomenon represented by physical object states and their change in time and, possibly, reflected in a time series of sensor reading values.

Note that the observability requirement excludes cognitive events such as "see" and "think."

2.1 Observable Events

WordNet [4] is an electronic lexical database in which English nouns, verbs, adjectives, and adverbs are organized into synonym sets, with each representing one underlying lexicalized concept, and with different relations linking the synonym sets. This means we can use WordNet to construct a representation that satisfies the above requirements. That is, we follow the strategy of collecting as many English words or phrases that denote physically observable events as possible using WordNet. We collect "observable" event concepts in the following way.

First, we set the twelve words shown in Table 1 as seeds. Six of them relate to "movements" and are selected on the basis of the description method of two dimensional movement trajectories [5] that show that a trajectory is expressed by the concatenation of "primitive" trajectories each of which has its own relation to the region illustrated in Figure 1. We add two words, "rise" and "drop," which represent gravitational movements and a word, "keep," which describes a state in which a certain movement continues. The other three words describe changes in physical scalar quantities such as temperature and light intensity. Incidentally, the words "rise," "drop," and "keep" also represent changes in physical scalar quantities. We expect the correct selection of the seeds to reduce the number of inappropriate words denoting cognitive events.

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Starting from the seed words, we traverse synonym links in WordNet and choose "observable" synonyms. For each word, WordNet generally contains two or more sets of synonyms; synonyms in a set hold an identical meaning and those in different sets have different meanings. For example, the word "displace" (which means to "remove or force from a prior position") has synonym sets including "dislodge" and "free" (which mean "remove or force from a position"), "shift," "dislodge," and "reposition" (which mean "change direction"), and "bump" and "knock" (which mean "knock against with force or violence"). We assume that synonyms that have the same meaning denote an identical event concept. We tag the concept with connected words that make up a phrase that describes the meaning written in WordNet; the words shift, dislodge, and reposition, for example, denote the event concept "change direction." We, therefore, deal with them as they denote the concept and label it with a phrase-like word change-direction. We say that each word shift, dislodge, and reposition is *associated with* the label change-direction.

Table 1. Seed words

on movement	on scalar quantities
move reach pass exit	*increase decrease remain*
touch enter rise drop keep	(*rise*) (*drop*) (*keep*)

Although this procedure eventually ends, we select the top five frequently occurring synonyms for each seed word that has, at most, three path lengths in WordNet. Because a further traversal of the synonym links produces cognitive words rather than observable event words, this restriction offers us an efficient synonym selection method that leads to the effective construction of a set comprising 185 labels (event concepts) and 348 words associated with the labels in total. We call the labels denoting event concepts the *base event-labels*.

The base event-labels permit us to construct *event descriptors* in the following way. First, we discriminate the base event-labels into two categories: transitive verb-phrase words and intransitive ones. The occurrence of an observable event labeled with a transitive verb-phrase word w corresponds to an action performance where an actor (mostly a person) performs an action related to an object. Thus, we obtain an event descriptor $w_{(a,o)}$, where a and o are slots or variables that denote an actor and an object, respectively. For example, change-location$_{(a,o)}$ is an event descriptor that denotes the event "someone moves something." On the other hand, in an observable event tagged with the intransitive word w, an object acts, thus we express it as $w_{(o)}$ or simply w. That is, we have an event descriptor change-location that denotes that "something moves" besides change-location$_{(a,o)}$.

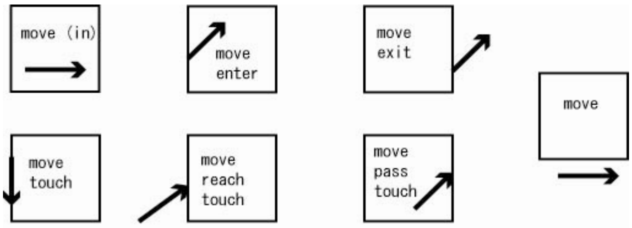


Fig. 1. "Primitive" trajectories (arrows) and their relations to a region (squares) [8]. The start and finish of the arrows represent those trajectories.

Second, we introduce argument notation. Some of the labeled event concepts involve implicit information about the time, space, and/or the properties of an object or a region. Because the physical quantity expression defined in Section 2.2 requires the explicit description of information, we introduce *words with arguments*, which enable us to express information explicitly. For example, "reach destination" implies that an object arrives at a region, thus from the label reach-destination, we obtain the event descriptor reach-destination(r:region), where an argument r denotes the region to be reached and region indicates the type of the argument r. A word associated with a label from which an event descriptor is constructed is also said to be *associated with* the event descriptor. Furthermore, we call a word associated with an event descriptor an *associated word*. Figure 2 shows the event descriptors and their associated words collected from the seed "reach."

Besides the event descriptors, we define *adjunct descriptors* or simply *adjuncts* that are derived from adverbs, prepositions, and nouns. That is, we define the adjuncts derived from local and temporal adverbs that are relatively high-frequency words: near(b:object), far(b:object), quickly, and slowly, common directional adverbs: vertically and horizontally, such temporal prepositions as $\mathrm{at}_t(\tau$:time) and $\mathrm{in}_t(\tau$:time), and such local prepositions as at_p(b:object), in_p(b:object), and on_p(b:object). To the adjuncts, we also add noun adjuncts derived from nouns. For example, adjuncts such as desk, chair, and door are derived from the nouns "desk," "chair," and "door," respectively. In particular, we assume that noun adjuncts derived from those denoting physical quantities as "temperature," "moisture," and "velocity" have arguments that, as their values, take adjuncts derived from nouns denoting physical objects. For example, temperature(o:object) is the adjunct derived from "temperature." Formally, the variables a and o in $w_{(a,o)}$ or

$w_{(o)}$ and those of words with arguments take noun adjuncts as their values.

Because many events occur at a certain time and location, we introduce a concatenation of an event descriptor and a local adjunct (and/or a temporal adjunct) that enables us to represent various event concepts. The concatenation

change-location$_{(\text{persona, bookB})}$ in$_p$(room C),

for example, represents "In room C, person A moves book B."

We recursively define an *observable event description* by an event descriptor or the concatenation of an observable event description and an adjunct descriptor. We call events denoted by an observable event description *observable events*. We identify an observable event description with the observable event itself in cases where no confusion exists.

be-in-direct-physical-contact-with(b:object) [touch, adjoin, meet, contact]
cause-to-move-by-striking$_{(a,o)}$ [hit]
come-to-be-adjacent-to(r:region) [converge, meet]
cover(r:region) [cover, extend]
extend-in-area$_{(a,o)}$ [widen, broaden, extend]
extend-out [exsert, stretch out, put out, extend, hold out, stretch forth]
extend-to(r:region) [reach, extend to, touch]
hit-against$_{(a,o)}$ [hit, strike, impinge on, run into, collide with]
increase$_{(a,o)}$(Q_s:scalarQuantity) [boost, advance, supercharge]
lie-adjacent-to(r:region) [border, adjoin, edge, abut, march, butt, butt against, butt on]
lie-adjacent-to-another(b:object) [border, adjoin, edge, abut, march, butt, butt against, butt on]
make-physical-contact-with$_{(a,o)}$ (b:object) [touch]
move-upward-in-order-to-touch(b:object) [reach, reach out]
occupy-as-of-space(r:region) [take, occupy, use up]
pass-into(r:region) [penetrate, perforate]
pass-through(r:region) [percolate, sink in, permeate, filter]
penetrate(b:object) [break through, come through]
reach-certain-state-in-time(s:state,t:time) [reach, hit, attain]
reach-destination(r:region) [reach, make, attain, hit, arrive at, gain, get, come]
reach-region-in-time(r:region,t:time) [reach, hit, attain]
stretch-out-over-space$_{(a,o)}$ [run, go, pass, lead, extend]
stretch-out-over-distance-between(b_1:object,b_2:object) [run, go, pass, lead, extend]
travel-across(r:region) [traverse, track, cover, cross, pass over, get over, get across, cut through, cut across]

Fig. 2. Event descriptors and their associated words (in brackets) that are collected from the seed "reach."

2.2 Expression Using Physical Quantities

The observability requirement implies the need to express each of the observable events using physical quantities such as the position, velocity, and temperature that represent the physical object states. As a first approximate expression, we assume that it is possible to assign the following simple form to each observable event,

$$\begin{aligned}\forall t((&t_0 \le t < t_1 \to P_1) \wedge \\ &(t_1 \le t \le t_2 \to P_2) \wedge \\ &(t_2 < t \le t_3 \to P_3)),\end{aligned}$$

where t_0, t_1, t_2, and t_3 are free variables and P_1, P_2, and P_3 are mathematical expressions including variables and physical constants that denote physical quantities such as position and temperature. In this form, the expression $t_0 \le t < t_1 \to P_1$ represents the *precondition* in which t is a parameter denoting time and P_1 expresses the physical state of objects connected with the event before the event occurs. The expression $t_1 \le t \le t_2 \to P_2$ specifies the *ongoing condition* in which the event starts at t_1 and finishes at t_2 and P_2 denotes the state change of the physical object. The last expression $t_2 \le t \le t_3 \to P_3$ describes the *post-condition*. Until t_3, the event result remains, which is expressed by P_3. Appendix describes the syntax of the physical quantity expression.

The assumption enables us to assign the same form to event descriptors. For example, we assign the event descriptor go-from-region-to-region(ρ_1:region,ρ_2:region) to the following expression:

$$\forall t\Big(\big(t_0 \le t < t_1 \to D(\lambda(t),\rho_1)=0\big) \wedge \big(t_1 \le t \le t_2 \to \left|\frac{d\lambda(t)}{dt}\right| > 0 \wedge D(\lambda(t),\rho_2) > 0\big) \wedge \big(t_2 < t \le t_3 \to D(\lambda(t),\rho_2)=0\big)\Big),$$

cause-to-move$_{(a,o)}$ [move, displace]

$$\frac{d\lambda(t)}{dt} = 0 \ (t_0 \le t < t_1), \left|\frac{d\lambda(t)}{dt}\right| > 0 \ (t_1 \le t \le t_2).$$

change-location [move, travel, go, locomote]

$$\left|\frac{d\lambda(t)}{dt}\right| > 0 \ (t_1 \le t \le t_2).$$

change-location$_{(a,o)}$ [move, travel, go, locomote]

$$\left|\frac{d\lambda(t)}{dt}\right| > 0 \ (t_1 \le t \le t_2).$$

drop-to-lower-place [sink, drop, drop down]

$$\frac{d\lambda(t)}{dt} \cdot g > 0 \wedge \frac{d^2\lambda(t)}{dt^2} = g \ (t_1 \le t \le t_2).$$

fall-vertically (drop)

$$\frac{\frac{d\lambda(t)}{dt}}{\left|\frac{d\lambda(t)}{dt}\right|} \cdot \frac{g}{|g|} = 1 \wedge \frac{d^2\lambda(t)}{dt^2} = g.$$

go-through(ρ:region) [pass, go through, go across]

$$D(\lambda(t),\rho) > 0 \ (t_0 \le t < t_1),$$
$$\left|\frac{\lambda(t)}{dt}\right| > 0 \wedge D(\lambda(t),\rho) = 0 \ (t_1 \le t \le t_2),$$
$$D(\lambda(t),\rho) > 0 \ (t_2 < t \le t_3),$$

move-upward$_{(a,o)}$ [lift, raise]

$$\frac{d\lambda(t)}{dt} \cdot g < 0 \ (t_1 \le t \le t_2).$$

reach-destination(ρ:region) [reach, make, attain, hit, arrive at, gain]

$$D(\lambda(t),\rho) > 0 \ (t_0 \le t < t_1),$$
$$\left|\frac{d\lambda(t)}{dt}\right| > 0 \wedge D(\lambda(t),\rho) > 0 \ (t_1 \le t \le t_2),$$
$$D(\lambda(t),\rho) = 0 \ (t_2 < t \le t_3),$$

raise-amount-of-something$_{(a,o)}$ (Q_s :scalarQuantity) [increase, raise]

$$\frac{d(Q_s(o))(t)}{dt} > 0 \ (t_1 \le t \le t_2).$$

become-separated-into-pieces [break, separate, split up, fall apart, come apart]

$$o = o_1 \cup o_2 \ \& \ o_1 \cap o_2 \ne 0 \ (t_0 \le t < t_1), \quad o = o_1 \cup o_2 \ \& \ o_1 \cap o_2 = 0 \ (t_2 < t \le t_3).$$

Fig. 3. The physical quantity expressions assigned to some of the event descriptors. Words in brackets are those associated with the event descriptors. The notation $\frac{d\lambda(t)}{dt} = 0 \ (t_0 \le t < t_1), \left|\frac{d\lambda(t)}{dt}\right| > 0 \ (t_1 \le t \le t_2),$ for example, is an abbreviation of $\forall t\left(\left(t_0 \le t < t_1 \to \frac{d\lambda(t)}{dt} = 0\right) \wedge \left(t_1 \le t \le t_2 \to \left|\frac{d\lambda(t)}{dt}\right| > 0\right) \wedge \left(t_2 < t \le t_3 \to true\right)\right).$

where $D(\rho_1, \rho_2)$ denotes the distance between regions ρ_1 and ρ_2 and $\lambda(t)$ is a special coordinate in a three-dimensional system at time t of the object that "goes from one region to another"; we assume that the object is a particle. Figure 3 exemplifies the physical quantity expressions assigned to some of the representative event descriptors together with their associated words.

We also assign the same types of expressions to the adjuncts derived from adverbs and prepositions. The adverb horizontally, for example, has the expression

$$\forall t((t'_0 \le t < t'_1 \to true) \wedge (t'_1 \le t \le t'_2 \to \frac{d\lambda(t)}{dt} \cdot \mathrm{g} = 0) \wedge (t'_2 < t \le t'_3 \to true)),$$

where g is the gravitational constant (vector) and the local preposition $\mathrm{in_p}$(b:object) has the same form:

$$\forall t((t'_0 \le t < t'_1 \to true) \wedge (t'_1 \le t \le t'_2 \to D(b, \lambda(t)) = 0) \wedge (t'_2 < t \le t'_3 \to true)).$$

The temporal preposition $\mathrm{at_t}(\tau$:time) has the expression

$$\forall t((t'_0 \le t < \tau \to true) \wedge (\tau \le t \le \tau \to true) \wedge (\tau < t \le t'_3 \to true)).$$

Now, let w be an event descriptor and p an adjunct. The physical quantity expression for a concatenation of w and p is defined by that of w "unified" with that of p. That is, let

$$\forall t((t_0 \le t < t_1 \to P_1) \wedge (t_1 \le t \le t_2 \to P_2) \wedge (t_2 < t \le t_3 \to P_3)),$$

be the physical quantity expression of w and

$$\forall t((t'_0 \le t < t'_1 \to P'_1) \wedge (t'_1 \le t \le t'_2 \to P'_2) \wedge (t'_2 < t \le t'_3 \to P'_3)),$$

be that of p. Then the physical quantity expression for a concatenation of w and p is defined by

$$\forall t((t'_0 \le t < t'_1 \to P_1 \wedge P'_1) \wedge (t'_1 \le t \le t'_2 \to P_2 \wedge P'_2) \wedge (t'_2 < t \le t'_3 \to P_3 \wedge P'_3)).$$

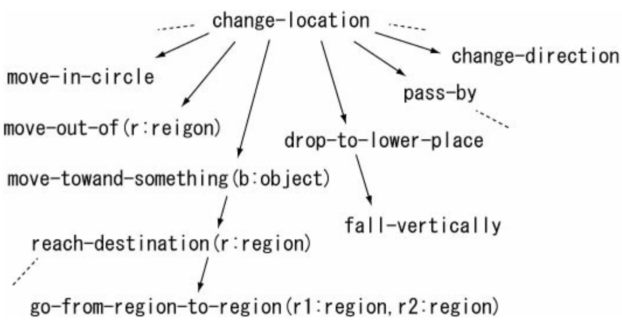
For example, the expression using physical quantities of the concatenation change-location $\mathrm{at_t}(\tau$:time) is

$$\forall t((t_0 \le t < \tau \to true) \wedge (\tau \le t \le \tau \to \left|\frac{d\lambda(t)}{dt}\right| > 0) \wedge (\tau < t \le t_3 \to true)).$$

Note that the rule for constructing a physical quantity expression for a concatenation follows the principle of compositionality in formal semantics (for example, [9]).

2.3 Ontological Structure

The event expression using physical quantities brings an ontological structure into the set of the event descriptors. The logical inclusion relationship between the two expressions by the representation defines a partial ordering in the event descriptor set. For example, let us consider the two event descriptors fall-vertically and change-location shown in Figure 3. As $\frac{\frac{d\lambda(t)}{dt}}{\left|\frac{d\lambda(t)}{dt}\right|} \cdot \frac{g}{|g|} = 1$ implies $\left|\frac{d\lambda(t)}{dt}\right| > 0,$ if the physical quantity expression [1] assigned to fall-vertically $\frac{\frac{d\lambda(t)}{dt}}{\left|\frac{d\lambda(t)}{dt}\right|} \cdot \frac{g}{|g|} = 1 \wedge \frac{d^2\lambda(t)}{dt^2} = g$ holds, so does that to change-location $\left|\frac{d\lambda(t)}{dt}\right| > 0$, which introduces the ontological relationship "is-a" between fall-vertically and change-location that defines a partial ordering between them. Likewise, in Figure 3, we can see such the "is-a" relation as move-upward *is a* change-location, fall-vertically *is a* drop-to-lower-place, and go-through *is a* change-location. Figure 4 illustrates a part of the event descriptor set with the partial ordering.



[1] We abbreviate the expression $\forall t((t_0 \le t < t_1) \to true \wedge (t_1 \le t \le t_2 \to P) \wedge (t_2 < t \le t_3 \to true))$ to P.

Fig. 4. The partial ordering set of event descriptors (a part). The arrows represent the relation “is-a.”

3. Application: Event Search System

The system consists of two modules: a query module and a search engine that refers to the sensor data grounder. Assuming an environment in which a sensor network always collects data produced by sensors attached to physical objects, the system returns information about an event that matches an intuitive interpretation of a set of NL words in a query.

The query module reads a query, which is a set of English words just like those used in Google, and translates the set into a description using an NL-like representation. For each description by the representation, an expression of physical quantities is assigned. The search engine searches the sensor database by contacting the sensor data grounder, which finds a data segment that satisfies the expression using the physical quantities that reflect the query conditions. Also, the query module answers by, for example, displaying a video image recorded by video cameras or by sending a reply via e-mail in English.

To demonstrate this system, we construct a sensor-networked office environment called s-room in which physical objects are equipped with sensor node including (a) micro-sensors such as a triaxial accelerometer, a thermometer, a hydrometer, an illuminator, and a human detector; and (b) wireless networking and computing engines for communicating with computing servers and other networked embedded objects such as the sensor database[7]. The environment is also equipped with the following: (a) an ultrasonic positioning system that enables us to locate eight or less movable objects; (b) an RFID system that permits us to identify persons with RFID tags in the environment; and (c) an object database that records the names, locations, and sizes of physical objects in the environment. Using a Web browser, users ask a query in a word set that contains a preposition and/or an adverb such as “who drop vase” or “when door open.” Users can also send a query by sending e-mail using a cellular phone.

4. Related Work

To specify complex and “higher-level” events, Jiao, Son, & Stankovic [8] developed an event-description language (SNEDL) based on Petri Net, which is a model for managing a system that has distributed, concurrent, asynchronous, and non deterministic features. SNEDL permits us to form a hierarchy of events. Li et al. [9] also designed a distributed index that scalably supports multi-dimensional range queries such as “List all events that have temperatures between 50℃ and 60℃, and light levels between 10 and 20 luces.”

The event-driven distributed model of the context-aware system proposed by Tan et al. [10] is leveraged on the event specification language and composite event detection algorithm. They classify events into primitive events and composite events that are constructed recursively by applying some operators to primitive and composite events. Primitive events are those low-level events that can be directly detected by sensors or other mechanisms embedded in the computing entities in the system. Composite events are events that are formed by applying a set of event operators such as “or,” “and,” or “seq(;)” to primitive and composite events. They also extend the context model with an event ontology so that event information can be retrieved from the infrastructure in a consistent and semantic way using SQL-like, not NL-like, semantic queries such as SELECT ?X WHERE (?X owl:hasTimeOfOccurrence>, “20.05.04 13:00:41").
Furthermore, to answer semantic queries, their system must infer events from sensor data in advance.

5. Concluding Remarks

This article presents an event representation together with a method that grounds sensor data. The event representation is a middle language between sensor reading values and NL–phrase descriptions. As an application using the event representation, this article also presents a system that searches sensor data that corresponds to real-world events using natural language (NL) words in a query.

Our own future research directs the following way: increasing event descriptors by introducing such other seeds such as “change” and some adjectives that represent the physical states of objects.

Appendix: The syntax of the physical quantity expression

A physical quantity expression is a form of

$$\forall t((t_0 \leq t < t_1 \rightarrow P_1) \wedge (t_1 \leq t \leq t_2 \rightarrow P_2) \wedge (t_2 < t \leq t_3 \rightarrow P_3)).$$

The mathematical expressions, P_1, P_2, and P_3, are E_1 & E_2 &…& $E_n (n \geq 1)$, where E_i, $i = 1, \ldots n$, take the forms of **calculus expressions** : $e_i > e'_i, e_i = e'_i$, or $e_i \neq e'_i$, where e_i, e'_i, are

1. constants: logical *true*, numerical ones, the gravitational vector **g**, and *Ground* denoting the ground plane,

2. variables:
   (a) those denoting physical quantities including as the position (λ), the temperature (T), the humidity (H), and the light intensity (L_u) is a term (and, for convenience, also the meta-variables whose values take variables denoting scalar (or vector) physical quantities).
   (b) those operated by scalar or vector operators such as the arithmetic operators ('+', '-', '*', '/'), the time differential $\left(\frac{d\,\cdot}{dt}\right)$, the time integral $\left(\int \cdot\, dt\right)$, the inner product $(\cdot)$, the norm $(|\cdot|)$, the vector projections to a coordinate axis or plane $(e.g., z(\cdot))$, the Euclidean distance $(D(\cdot,\cdot))$ and
   (c) those operated by operator compositions such as $\left|\frac{d\,\cdot}{dt}\right|$ and $\frac{d\,\cdot}{dt}\cdot\frac{d\,\cdot}{dt'}$, or

set expressions : $e_i \in e'_i, e_i \notin e'_i$, or $e_i \subset e'_i$, where e_i, e'_i are

1. the empty set 0,
2. variables:
   (a) those denoting sets of regions or those occupied by objects in the three dimensional space or
   (b) those operated by $\cap$, $\cup$, and $-$ on two sets of regions or those occupied by objects in the three-dimensional space.

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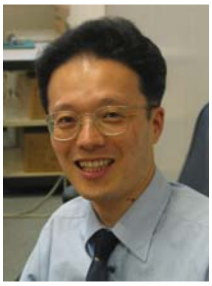

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