An Approach to Natural Language Understanding Based on a Mental Image Model

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Abstract. The Mental Image Directed Semantic Theory (MIDST) has proposed an omnisensual mental image model and its description language L_{md}. This paper presents a brief sketch of the MIDST, and focuses on word meaning description and text understanding in association with the mental image model in view of cross-media reference between text and picture.

1 Introduction

The need for more human-friendly intelligent systems has been brought by rapid increase of aged societies, floods of multimedia information over the WWW, development of robots for practical use and so on.

For example, it is very difficult for people to exploit necessary information from the immense multimedia contents over the WWW. It is still more difficult to search for desirable contents by queries in different media, for example, text queries for pictorial contents. In this case, intelligent systems facilitating cross-media reference are very helpful.

In order to realize these kinds of intelligent systems, we think it is very important to develop such a computable knowledge representation language for multimedia contents that should have at least a capability of representing spatio-temporal events that people perceive in the real world. In this research area, it is most conventional that conceptual contents conveyed by information media such as language and picture are represented in computable forms independent of each other and translated via 'transfer' processes which are often specific to task domains [10], [11].

Yokota, M. et al have proposed a semantic theory of natural language based on an omnisensual image model, so called, 'Mental Image Directed Semantic Theory (MIDST)' [1]. In the MIDST, the concepts conveyed by such syntactic components as words, phrases, clauses and so on are associated with mental imagery of the external or physical world and formalized in an intermediate language L_{md} [3].

L_{md} is employed for many-sorted predicate logic with five types of terms. The most remarkable feature of L_{md} is its capability of formalizing both temporal and spatial

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event concepts on the level of human sensations while the other similar knowledge representation languages are designed to describe the logical relations among conceptual primitives represented by lexical tokens [5], [6], [7].

The language $\boldsymbol{L_{md}}$ has already been implemented on several versions of the intelligent system IMAGES [1], [2], [3], [4] and there is a feedback loop between them for their mutual refinement, unlike the other similar ones [8], [9].

This paper presents a brief sketch of the MIDST, and focuses on word meaning description and text understanding in association with the mental image model in view of cross-media reference between text and picture.

2 A Brief Sketch of MIDST

The MIDST is still under development and intended to provide a formal system, represented in $\boldsymbol{L_{md}}$, for natural semantics of space and time. This system is one kind of applied predicate logic consisting of axioms and postulates subject to human perceptive processes of space and time, while the other similar systems in Artificial Intelligence [12], [13], [14] are objective, namely, independent of human perception and do not necessarily keep tight correspondences with natural language.

2.1 Omnisensual image model

The MIDST treats word meanings in association with mental images, not limited to visual but omnisensual, modeled as "Loci in Attribute Spaces" [1], [2], [3], [4]. An attribute space corresponds with a certain measuring instrument just like a barometer, a map measurer or so and the loci represent the movements of its indicator.

For example, the moving black triangular object shown in Fig.1-a is assumed to be perceived as the loci in the three attribute spaces, namely, those of 'Location', 'Color' and 'Shape' in the observer's brain.

A general locus is to be articulated by "Atomic Locus" with the duration $[t_i, t_f]$ as depicted in Fig.1-b and formalized as (1).

$$L(x,y,p,q,a,g,k) \qquad (1)$$

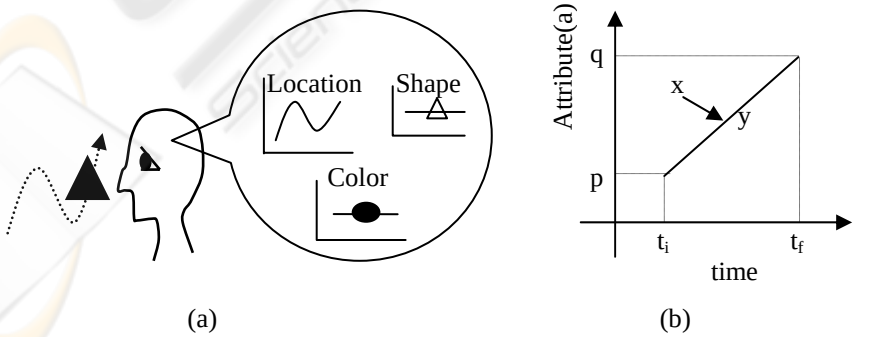


Fig.1. Mental image model: (a) Attribute spaces and (b) Atomic locus.

This is a formula in many-sorted first-order predicate logic, where "L" is a predicate constant with five types of terms: "Matter" (at 'x' and 'y'), "Attribute Value" (at 'p' and 'q'), "Attribute" (at 'a'), "Event Type" (at 'g') and "Standard" (at 'k'). Conventionally, Matter variables are headed by 'x', 'y' and 'z' and often placed at Attribute Values or Standard to represent their values at the time. The formula is called 'Atomic Locus Formula' whose first two arguments are sometimes referred to as 'Event Causer (EC)' and 'Attribute Carrier (AC)', respectively.

The intuitive interpretation of (1) is given as follows, where 'matter' refers approximately to 'object' or 'event'.

"Matter 'x' causes Attribute 'a' of Matter 'y' to keep (p=q) or change (p ≠ q) its values temporally (g=Gt) or spatially (g=Gs) over a time-interval, where the values 'p' and 'q' are relative to the standard 'k'."

When $g=Gt$ and $g=Gs$, the locus indicates monotonic change or constancy of the attribute in time domain and that in space domain, respectively. The former is called 'temporal event' and the latter, 'spatial event'.

For example, the motion of the 'bus' represented by S1 is a temporal event and the ranging or extension of the 'road' by S2 is a spatial event whose meanings or concepts are formalized as (2) and (3), respectively, where the attribute is 'Physical Location' denoted by 'A12'.

(S1) The bus runs from Tokyo to Osaka.

$$(\exists x,y,k)L(x,y,Tokyo,Osaka,A12,Gt,k)\wedge bus(y) \quad (2)$$

(S2) The road runs from Tokyo to Osaka.

$$(\exists x,y,k)L(x,y,Tokyo,Osaka,A12,Gs,k)\wedge road(y) \quad (3)$$

2.2 Tempo-logical connectives

The duration of an atomic locus, suppressed in the atomic locus formula, corresponds to the time-interval over which the Focus of the Attention of the Observer (FAO) is put on the corresponding phenomenon outside.

The MIDST has employed 'tempo-logical' connectives representing both logical and temporal relations between loci. A tempo-logical connective K_i is defined by (4), where τ_i, χ and K refer to one of the temporal relations indexed by 'i', a locus, and an ordinary binary logical connective such as the conjunctive '$\wedge$', respectively. This is more natural and economical than explicit indication of time intervals, considering that people do not consult chronometers all the time in their daily lives.

The expression (5) is the conceptual description of the English verb 'fetch' depicted as Fig.2-a, implying such a temporal event that 'x' goes for 'y' and then comes back with it, where 'Π'and '•' are instances of the tempo-logical connectives, 'SAND' and 'CAND', standing for 'Simultaneous AND' and 'Consecutive AND', respectively. In general, a series of atomic locus formulas with such connectives is simply called 'Locus formula'.

$$\chi_1 K_i \chi_2 \Leftrightarrow (\chi_1 K \chi_2) \wedge \tau_i(\chi_1, \chi_2) \quad (4)$$

$$(\exists x,y,p1,p2,k)\, L(x,x,p1,p2,A12,Gt,k) \bullet ((L(x,x,p2,p1,A12,Gt,k) \Pi L(x,y,p2,p1,A12,Gt,k)) \wedge x\neq y \wedge p1\neq p2 \quad (5)$$

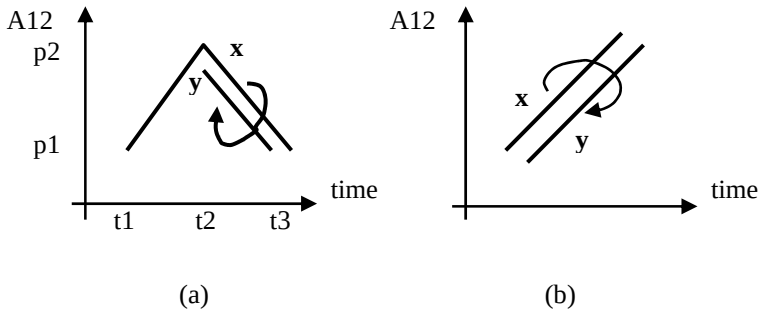


Fig.2. Conceptual images: (a) 'fetch' and (b) 'carry'.

Additionally, Fig.2-b shows the conceptual image of the English verb 'carry' that is also included in the conceptual image of 'fetch'. These are called 'Event Patterns' and about 40 kinds of event patterns have been found concerning the attribute 'Physical Location (A12)', for example, *start*, *stop*, *meet*, *separate*, *return*, etc [1].

Furthermore, a very important concept called 'Empty Event (EE)' and symbolized as 'ε' is introduced. An EE stands for nothing but for time collapsing and is explicitly defined as (6) with the attribute 'Time Point (A34)'. It is essentially significant for the MIDST that ***every temporal relation can be represented by a combination of Empty Events, SANDs and CANDs***. For example, (7) represents 'X_1 during X_2'.

According to this scheme, the duration [*p, q*] of an arbitrary locus X can be expressed as (8).

$$\varepsilon \Leftrightarrow (\exists x,y,p,q,g,k)\, L(x,y,p,q,A34,g,k) \quad (6)$$

$$(\varepsilon_1 \bullet X_1 \bullet \varepsilon_2)\ \Pi\ X_2 \quad (7)$$

$$X\ \Pi\ \varepsilon(p,q) \quad (8)$$

2.3 Event types

It has been often argued that human active sensing processes may affect perception and in turn conceptualization and recognition of the physical world. The difference between temporal and spatial event concepts can be attributed to the relationship between the Attribute Carrier (AC) and the Focus of the Attention of the Observer (FAO). To be brief, the FAO is fixed on the whole AC in a temporal event but *runs* about on the AC in a spatial event.

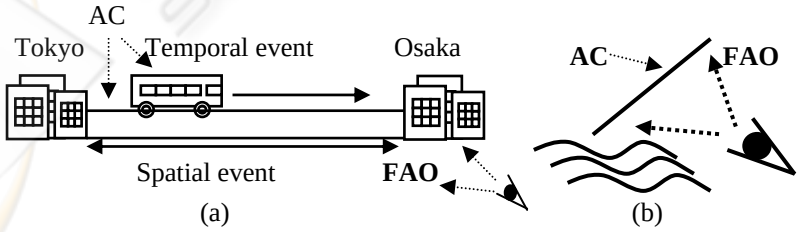


Fig.3. FAO movement: (a) event types and (b) 'slope' as a spatial event.

Consequently, as shown in Fig.3-a, the *bus* and the FAO move together in the case of S1 while the FAO solely moves along the *road* in the case of S2. That is, ***all loci in Attribute spaces correspond one to one with movements or, more generally, temporal events of the FAO***.

Therefore, S3 and S4 refer to the same scene in spite of their appearances as shown in Fig.3-b where, as easily imagined, what 'sinks' or 'rises' is the FAO, and whose conceptual descriptions are given as (9) and (10), respectively.

Such a fact is generalized as ' ***Postulate of Reversibility of a Spatial event*** (PRS) ' that can be one of the principal inference rules belonging to people's common-sense knowledge about geography. This postulation is also valid for such a pair of S5 and S6 interpreted as (11) and (12), respectively, where 'A13', '↑' and '↓' refer to the attribute 'Direction' and its values 'upward' and 'downward', respectively. These pairs of conceptual descriptions are called ***equivalent in the PRS***, and the paired sentences are treated as ***paraphrases*** each other.

(S3) The path *sinks to* the brook.

$$(\exists x,y,p,z,k1,k2)L(x,y,p,z,A12,Gs,k1)$$
$$\Pi L(x,y,\downarrow,\downarrow,A13,Gs,k2)\wedge path(y)\wedge brook(z)\wedge p\neq z \quad (9)$$

(S4) The path *rises from* the brook.

$$(\exists x,y,p,z,k1,k2)L(x,y,z,p,A12,Gs,k1)$$
$$\Pi L(x,y,\uparrow,\uparrow,A13,Gs,k2)\wedge path(y)\wedge brook(z)\wedge p\neq z \quad (10)$$

(S5) Route A and Route B meet at the city.

$$(\exists x,p,y,q,k)L(x,Route\_A,p,y,A12,Gs,k)$$
$$\Pi L(x,Route\_B,q,y,A12,Gs,k)\wedge city(y)\wedge p\neq q \quad (11)$$

(S6) Route A and Route B separate at the city.

$$(\exists x,p,y,q,k)L(x,Route\_A,y,p,A12,Gs,k)$$
$$\Pi L(x,Route\_B,y,q,A12,Gs,k)\wedge city(y)\wedge p\neq q \quad (12)$$

2.4 Attributes and standards

The attribute spaces for humans correspond to the sensory receptive fields in their brains. At present, about 50 attributes concerning the physical world have been extracted exclusively from English and Japanese words as shown in Table 1. They are associated with all of the 5 senses (i.e. sight, hearing, smell, taste and feeling) in our everyday life while those for information media other than languages correspond to limited senses. For example, those for pictorial media, marked with '*' in Table 1, associate limitedly with the sense 'sight' as a matter of course. The attributes of this sense occupy the greater part of all, which implies that the sight is essential for humans to conceptualize the external world by. And this kind of classification of attributes plays a very important role in our cross-media referencing system [3].

Correspondingly, six categories of standards shown in Table 2 have been extracted that are assumed necessary for representing values of each attribute in Table 1. In general, the attribute values represented by words are relative to certain standards as explained briefly in Table 2.

Table 1. A part of attributes extracted from linguistic expressions.
[+]The properties "S" and "V" represent "scalar" and "vector", respectively.

Code	Attribute [Property]	Linguistic expressions for attribute values.
*A01	PLACE OF EXISTE NCE [V]	He is in Tokyo. The accident happened in Osaka.
*A02	LENGTH [S]	The stick is 2 meters long (in length).
	……	
*A12	PHYSICAL LOCATION [V]	Tom moved to Tokyo.
*A13	DIRECTION [V]	The box is to the left of the chair.
*A14	ORIENTATION [V]	The door faces to south.
*A15	TRAJECTORY [V]	The plane circled in the sky.
*A16	VELOCITY [S]	The boy runs very fast.
*A17	DISTANCE [S]	The car ran ten miles.
A18	STRENGTH OF EFFECT [S]	He is very strong.
	……	
*A32	COLOR [V]	The apple is red. Tom painted the desk white.
A33	INTERNAL SENSATION [V]	I am very tired.
A34	TIME POINT [S]	It is ten o'clock.
	……	

Table 2. Standards of attribute values.

Categories of standards	Remarks
Rigid Standard	Objective standards such as denoted by measuring *units* (meter, gram, etc.).
Species Standard	The *attribute value ordinary* for a species. A *short train* is ordinarily longer than a *l ong pencil*.
Proportional Stand ard	'*Oblong*' means that the width is greater than the height at a physical object.
Individual Standard	*Much* money for one person can be too *little* for another.
Purposive Standard	One room large enough for a person's *sleeping* must be too small for his *jogging*.
Declarative Standar d	The origin of an order such as 'next' must be declared explicitly just as 'next *to him* '

3 Word meaning description

A word meaning description M_w is given by (13) as a pair of 'Concept Part (C_p)' and 'Unification Part (U_p)'.

$$M_w \Leftrightarrow [C_p : U_p] \tag{13}$$

The C_p of a word W is a logical formula while its U_p is a set of operations for unifying the C_ps of W's syntactic governors or dependents. For example, the meaning of the English verb 'carry' is approximately given by (14).

$$[(\exists x,y,p1,p2,k)\, L(x,x,p1,p2,A12,Gt,k) \Pi L(x,y,p1,p2,A12,Gt,k) \wedge x \neq y \wedge p1 \neq p2: ARG(Dep.1,x);\ ARG(Dep.2,y);] \tag{14}$$

The U_p above consists of two operations to unify the arguments of the first dependent (Dep.1) and the second dependent (Dep.2) of the current word with the variables x and y, respectively. Here, Dep.1 and Dep.2 refer to the 'subject' and the 'object' of 'carry', respectively. Therefore, the sentence '*Mary carries a book*' is translated into (15).

$(\exists y,p1,p2,k)\ L(Mary,Mary,p1,p2,A12,Gt,k) \Pi L(Mary,y,p1,p2,A12,Gt,k)$
$\wedge Mary \neq y\ \wedge p1 \neq p2\ \wedge book(y)$ (15)

For another example, the meaning description of the English preposition 'through' is also approximately given by (16).

$[(\exists x,y,p1,z,p3,g,k,p4,k0)\ (\underline{L(x,y,p1,z,A12,g,k)} \bullet L(x,y,z,p3,A12,g,k))$
$\Pi L(x,y,p4,p4,A13,g,k0)\ \wedge p1 \neq z\ \wedge z \neq p3$: $ARG(Dep.1,z)$;
$IF(Gov=Verb) \rightarrow PAT(Gov,(1,1))$; $IF(Gov=Noun) \rightarrow ARG(Gov,y)$;] (16)

The U_p above is for unifying the C_ps of the very word, its governor (Gov, a verb or a noun) and its dependent (Dep.1, a noun). The second argument (1,1) of the command PAT indicates the underlined part of (16) and in general (i,j) refers to the partial formula covering from the ith to the jth atomic formula of the current C_p. This part is the pattern common to both the C_ps to be unified. This is called 'Unification Handle (U_h)' and when missing, the C_ps are to be combined simply with '$\wedge$'.

Therefore the sentences S7, S8 and S9 are interpreted as (17), (18) and (19), respectively. The underlined parts of these formulas are the results of PAT operations. The expression (20) is the C_p of the adjective 'long' implying 'there is some value greater than some standard of length (A02)' which is often simplified as (20').

(S7) The train runs through the tunnel.

$(\exists x,y,p1,z,p3,k,p4,k0)\ (\underline{L(x,y,p1,z,A12,Gt,k)} \bullet L(x,y,z,p3,A12,Gt,k))$
$\Pi L(x,y,p4,p4,A13,Gt,k0)\ \wedge p1 \neq z\ \wedge z \neq p3\ \wedge train(y)\ \wedge tunnel(z)$ (17)

(S8) The path runs through the forest.

$(\exists x,y,p1,z,p3,k,p4,k0)\ (\underline{L(x,y,p1,z,A12,Gs,k)} \bullet L(x,y,z,p3,A12,Gs,k))$
$\Pi L(x,y,p4,p4,A13,Gs,k0)\ \wedge p1 \neq z\ \wedge z \neq p3\ \wedge path(y)\ \wedge forest(z)$ (18)

(S9) The path through the forest is long.

$(\exists x,y,p1,z,p3,x1,k,q,k1,p4,k0)\ (L(x,y,p1,z,A12,Gs,k) \bullet L(x,y,z,p3,A12,Gs,k))$
$\Pi L(x,y,p4,p4,A13,Gs,k0)\ \wedge L(x1,y,q,q,A02,Gt,k1)$
$\wedge p1 \neq z\ \wedge z \neq p3\ \wedge\ q > k1\ \wedge path(y)\ \wedge forest(z)$ (19)
$(\exists x1,y1,q,k1) L(x1,y1,q,q,A02,Gt,k1) \wedge q > k1$ (20)
$(\exists x1,y1,k1) L(x1,y1,Long,Long,A02,Gt,k1)$ (20')

4 Text Understanding and Cross-Media Reference

Every version of the intelligent system IMAGES can perform text understanding based on word meaning descriptions as follows.

Firstly, a text is parsed into a surface dependency structure (or more than one if *syntactically* ambiguous). Secondly, each surface dependency structure is translated into a conceptual structure (or more than one if *semantically* ambiguous) using word meaning descriptions. Finally, each conceptual structure is semantically evaluated.

The fundamental semantic computations on a text are to detect semantic anomalies, ambiguities and paraphrase relations.

Semantic anomaly detection is very important to cut off meaningless computations. Consider such a conceptual structure as (21), where 'A29' is the attribute 'Taste'. This locus formula can correspond to the English sentence 'The desk is sweet', which is usually semantically anomalous because a 'desk' *ordinarily* has no taste.

$(\exists x)L(\_,x,Sweet,Sweet,A29,Gt,\_)\wedge desk(x)$ (21)

This kind of semantic anomaly can be detected in the following process.

Firstly, assume the commonsense knowledge of 'desk' as (22), where 'A39' refers to the attribute 'Vitality'. The special symbols '*' and '/' are defined as (23) and (24) representing 'always' and 'no value', respectively. Another special symbol '_' defined by (25) is often used instead of the variable bound by an existential quantifier.

$(\lambda x)\ desk(x) \leftrightarrow (\lambda x)\ (\ldots L^*(\_,x,/,/,A29,Gt,\_)$

$\wedge\ldots\wedge L^*(\_,x,/,/,A39,Gt,\_)\wedge\ldots)$ (22)

$X^* \leftrightarrow (\forall p,q)X\ \Pi\varepsilon(p,q)$ (23)

$L(\ldots,/,\ldots) \leftrightarrow \sim(\exists p)\ L(\ldots,p,\ldots)$ (24)

$L(\ldots,\_,\ldots) \leftrightarrow (\exists x)L(\ldots,x,\ldots)$ (25)

Secondly, the postulates (26) and (27) are utilized. The formula (26) means that ***if one of two loci exists every time interval, then they can coexist***. The formula (27) states that ***a matter has never different values of an attribute at a time***.

$X \wedge Y^* .\supset. X\ \Pi Y$ (26)

$L(x,y,p1,q1,a,g,k)\ \Pi L(z,y,p2,q2,a,g,k)\ .\supset.\ p1=p2\wedge q1=q2$ (27)

Lastly, the semantic anomaly of 'sweet desk' is detected by using (21)-(27). That is, the formula (28) below is finally deduced from (21)-(26) and violates the commonsense given by (27), that is, " $Sweet \neq /$ ".

$(\exists x)L(\_,x,Sweet,Sweet,A29,Gt,\_)\ \Pi L(\_,x,/,/,A29,Gt,\_)$ (28)

This process above is also employed for dissolving such a syntactic ambiguity as found in S10. That is, the semantic anomaly of 'sweet desk' is detected and eventually 'sweet coffee' is adopted as a plausible interpretation.

(S10) Bring me the coffee on the desk, which is sweet.

If a text has multiple plausible interpretations, it is semantically ambiguous. In this case, IMAGES will ask for further information in order for disambiguation.

For another case, if two different texts are interpreted into the same locus formula, they are paraphrases of each other. The detection of paraphrase relations is very useful for deleting redundant information.

IMAGES-M [3], the last version of IMAGES, can perform cross-media reference between text and picture. For example, consider such somewhat complicated sentences as S11 and S12. The underlined parts are considered to refer to some events neglected in time and in space. These events are called 'Temporal Empty Event (TEE)' and 'Spatial Empty Event (SEE)', symbolized as 'ε_t' and 'ε_s', respectively.

The concepts of S11 and S12 are given by (29) and (30) with the attribute 'Trajectory (A15)'.

(S11) The *bus* runs 10km straight east from A to B, and <u>*after a while*</u>, at C it meets the street with the sidewalk.

$(\exists x,y,z,p,q)\ (L(\_,x,A,B,A12,Gt,\_)\ \Pi L(\_,x,0,10km,A17,Gt,\_)$

$\Pi L(\_,x,Point,Line,A15,Gt,\_)\Pi L(\_,x,East,East,A13,Gt,\_))$

$\bullet\ \varepsilon_t\ \bullet\ (L(\_,x,p,C,A12,Gt,\_)\ \Pi L(\_,y,q,C,A12,Gs,\_)\Pi L(\_,z,y,y,A12,Gs,\_))$

$\wedge bus(x)\wedge street(y)\wedge sidewalk(z)\wedge p\neq q$ (29)

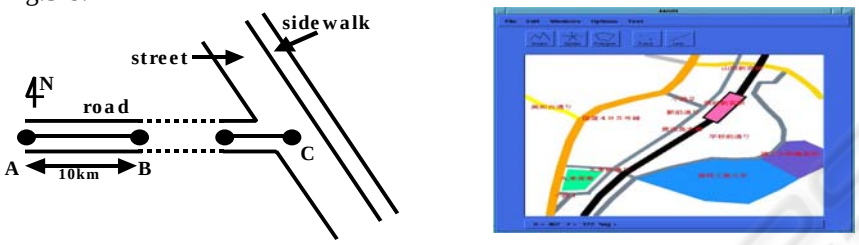
(S12) The *road* runs 10km straight east from A to B, and <u>*after a while*</u>, at C it meets the street with the sidewalk.

$(\exists x,y,z,p,q)(L(\_,x,A,B,A12,Gs,\_)\ \Pi L(\_,x,0,10km,A17,Gs,\_)$

$\Pi L(\_,x,Point,Line,A15,Gs,\_)\Pi L(\_,x,East,East,A13,Gs,\_))$

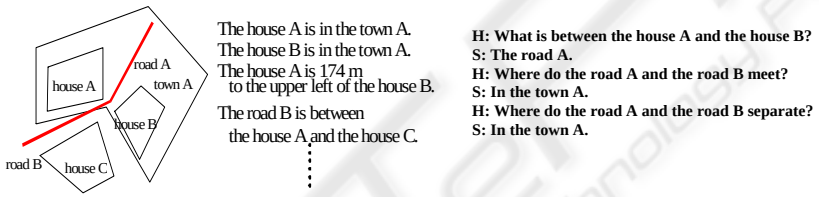
$$\bullet\, \varepsilon_s \bullet (L(\_,x,p,C,A12,Gs,\_)\ \Pi TL(\_,y,q,C,A12,Gs,\_)\Pi TL(\_,z,y,y,A12,Gs,\_)) \wedge road(x) \wedge street(y) \wedge sidewalk(z) \wedge p \neq q \quad (30)$$

From the viewpoint of cross-media reference, the formula (30) can refer to such a spatial event depicted as the still picture in Fig.4-a while (29) can be interpreted into a motion picture. Figure 4-b shows one of real maps that IMAGES-M generated from their corresponding locus formulas. IMAGES-M can also translate pictures into texts via locus formulas as shown in Fig.5-a and answer questions about pictures as shown in Fig.5-b.



(a) (b)

Fig. 4. Pictorial interpretations of locus formulas: (a) an illustration of (30) and (b) a real output of IMAGES-M.



(a) (b)

Fig. 5 Cross-media operations: (a) picture-to-text translation and (b) Q-A on the picture where 'H' and 'S' stand for 'Human' and 'System', respectively.

5 Discussions and Conclusions

The attribute spaces for humans correspond to the sensory receptive fields in their brains. At present, about 50 attributes and 6 categories of standards concerning the physical world have been extracted from a Japanese and an English thesaurus. Event patterns such as shown in Fig.2 are the most important for our approach and have been already reported concerning several kinds of attributes [1], [2]. The cross-references between texts in several languages (Japanese, Chinese, Albanian and English) and pictorial patterns like maps were successfully implemented on our intelligent system IMAGES-M. At our best knowledge, there is no other system that can perform cross-media reference in such a seamless way as ours [15], [16]. This leads to the conclusion that our locus formula representation has made the logical expressions of event concepts remarkably computable and has proved to be very adequate to systematize cross-media reference. This adequacy is due to its medium-freeness and its good correspondence with the performances of human sensory systems in both spatial

and temporal extents while almost all other knowledge representation schemes are ontology-dependent or spatial-event-unconscious.

Our future work will include establishment of learning facilities for automatic acquisition of word concepts from sensory data [2] and human-robot communication by natural language under real environments [4].

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