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先行予測反応システム

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> 「先発すれば人を制し；後発すれば人に制せらる。」
> ー 班彪，班固，班昭：『漢書』，紀年82年頃.

あらまし 従来の反応的システムは、外部からの刺激に対して受動的にしか反応できないので、信頼性と安全性から見れば、いつも受け身になっており、災害や攻撃を事前に能動的に自己防衛することができない。本論文は、次世代高信頼性・高安全性システムとして先行予測反応システムを提案し、その構成原理、論理基礎、実現技術、および可能な応用を論じる。先行予測反応システムは、従来の反応的システムに新たにシステムの外部環境変化の数理モデルおよび時間相関論理に基づく先行予測推論エンジンを付け加え、システム内部状態と外部環境の変化を計測、監視しながら、災害や攻撃の兆候を検出し、先行予測推論の結果に基づいて、災害や攻撃による損害をできるだけ未然に防ぐことを目指している。

キーワード 反応的システム，高信頼性システム，高安全性システム，先行性，先行予測推論，時間相関論理

Anticipatory Reasoning-Reacting Systems

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> **"Taking the anticipation, you will forestall your enemy;**
> **losing the initiative, you will be controlled by your enemy."**
> **– Ban Biao, Ban Gu, and Ban Zhao,**
> **"The Han Shu (The Book of Han)", about A.D. 82.**

Abstract The next generation of reactive systems should be more active and anticipatory than the traditional systems in order to satisfy the requirements of high reliability and high security from advanced applications of reactive systems. This paper proposes a new type of reactive systems, named "Anticipatory Reasoning-Reacting Systems," as a certain class of anticipatory systems. The paper presents the background and motivation to develop anticipatory reasoning-reacting systems, proposes the architecture and logical basis of the systems, and shows their implementation problems and possible applications.

Keyword Reactive systems, Highly reliable systems, Highly secure systems, Anticipation, Anticipatory reasoning, Temporal relevant logic

1. Introduction

A reactive system is a computing system that maintains an ongoing interaction with its environment as opposed to computing some final value on termination [13, 14]. Typical examples of reactive systems are: computer operating systems, computer networks, digital libraries, airplane and train traffic control systems, nuclear reactor control systems, and various embedded and process control systems. Modern information society is more and more dependent on various reactive systems, and, of course, dependent on the continuous, reliable, and secure functioning of the systems. Since a breakdown of a reactive system running world-wide may be disastrous to our lives, how to design, develop, and maintain highly reliable and highly secure reactive systems has become a very important issue in not only computer science and engineering but also systems science and engineering.

Almost all reactive systems developed until now are passive, i.e., the systems only can perform those operations in response to instructions explicitly issued by users or application programs, but have no ability to do something actively and anticipatorily by themselves. However, from the viewpoint of information security engineering, a traditional passive reactive system only has some quite weak capability to defend attacks from its external computing environment. In order to prevent attacks beforehand, it is to be desired that a reactive system can detect and predict omens of attacks anticipatorily and then take some actions to inform its users and perform some operations to defend attacks by itself. On the other hand, those reactive systems with highly reliable requirements also need some anticipatory mechanism to prevent disasters beforehand.

The next generation of reactive systems should be more active and anticipatory than the traditional systems in order to satisfy the requirements from advanced applications of reactive systems. This paper proposes a new type of reactive systems, named *"Anticipatory Reasoning-Reacting Systems,"* as a certain class of anticipatory systems. The paper presents the background and motivation to develop anticipatory reasoning-reacting systems, proposes the architecture and logical basis of the systems, and shows their implementation problems and possible applications.

2. Anticipatory Reasoning-Reacting Systems

The concept of an anticipatory system first proposed by theoretical biologist Rosen in 1980s [17, 18]. Rosen considered that "an anticipatory systems is one in which present change of state depends upon future circumstance, rather than merely on the present or past" and defined an anticipatory system as "a system containing a predictive model of itself and/or its environment, which allows it to change state at an instant in accord with the model's prediction to a latter instant." [18] Until now, philosophical discussions on anticipatory systems and their characteristics are still being continued by scientists from various disciplines [9, 11, 12, 15, 16].

On the other hand, from the viewpoints of software engineering and information security engineering, what we need is really useful systems with anticipatorily predictive capability to take anticipation for forestalling disasters and attacks rather then the philosophical definition and intension of an anticipatory system. In order to develop anticipatory systems useful in the real world, we now propose the following constructive definition for a certain class of anticipatory systems which the present author considers to be possible.

An ***anticipatory reasoning-reacting system*** (ARRS for short) is a computing system containing a controller C with capabilities to measure and monitor the behavior of the whole system, a traditional reactive system RS, a predictive model PM of RS and its external computing environment, and an anticipatory reasoning engine ARE such that according to predictions by ARE based on PM, C can order and control RS to carry out some operations with a high priority.

Our definition of an ARRS makes the following points explicit: First, an ARRS is a computational system which can run on computers and computer networks. Second, an ARRS is a simple extension of a traditional reactive system by introducing a central controller, a predictive model, and an anticipatory reasoning engine. Third, an ARRS takes anticipation by anticipatory reasoning based on the predictive model, i.e., reasoning is the only way to take anticipation.

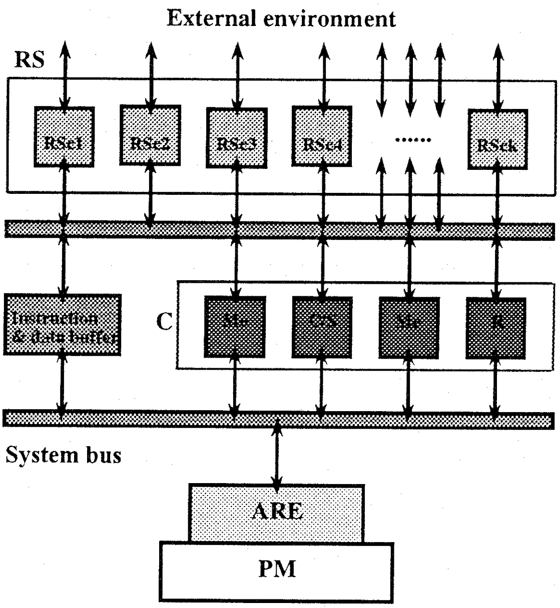

Fig. 1 The architecture of an ARRS

Fig. 1 shows the architecture of an ARRS. It is based on the above definition of ARRS and the present author's following considerations.

The dependence principle in measuring, monitoring, and controlling: "Any system cannot control what it cannot measure and monitor."

The wholeness principle of concurrent systems: "The behavior of a concurrent system is not simply the mechanical putting together of its parts that act concurrently but a whole such that one cannot find some way to resolve it into parts mechanically and then simply compose the sum of its parts as the same as its original behavior." [5, 6]

The uncertainty principle in measuring and monitoring concurrent systems: "The behavior of an observer such as a run-time measurer or monitor cannot be separated from what is being observed." [5, 6]

The self-measurement principle in designing, developing, and maintaining concurrent systems: "A large-scale, long-lived, and highly reliable concurrent system should be constructed by some function components and some (maybe only one) permanent self-measurement components that act concurrently with the function components, measure and monitor the system itself according to some requirements, and pass run-time information about the system's behavior to the outside world of the system." [5, 6]

According to our definition of an ARRS, it is obvious that an ARRS can work well and therefore useful to advanced applications in the real world only if it can reason out precise predictions and take some anticipatory actions according to the predictions. Therefore, the most intrinsically important components in an ARRS are the predictive model PM and the anticipatory reasoning engine ARE. The predictive model must be dependent on the reactive system RS and its application area, while the anticipatory reasoning engine may be an application-independent general one. Since anticipatory reasoning based on the predictive model is the only way for the system to reason out predictions, both the predictive model PM and the anticipatory reasoning engine ARE must be based on a sound logical basis.

3. Temporal Relevant Logic as the Logical Basis of ARRSs

We now propose the logical basis of ARRSs which probably is the most fundamental theory to underlie the systems and their applications.

Reasoning is the ***process*** of drawing ***new conclusions*** from given premises, which are already known facts or previously assumed hypotheses (Note that how to define the notion of "new" formally and satisfactorily is still a difficult open problem until now). Therefore, reasoning is intrinsically ampliative, i.e., it has the function of enlarging or extending some things, or adding to what is already known or assumed. In general, a reasoning consists of a number of arguments (or inferences) ***in some order***. An ***argument*** (or ***inference***) is a set of declarative sentences consisting of one or more sentences as its premises, which contain the evidence, and one sentence as its conclusion. In an argument, a claim is being made that there is some sort of ***evidential relation*** between its premises and its conclusion: the conclusion is supposed to ***follow from*** the premises, or equivalently, the premises are supposed to ***entail*** the conclusion. Therefore, the correctness of an argument is a matter of the ***connection*** between its premises and its conclusion, and concerns the ***strength*** of the relation between them (Note that the correctness of an argument depends neither on whether the premises are really true or not, nor on whether the conclusion is really true or not). Thus, there are some fundamental questions: What is the criterion by which one can decide whether the conclusion of an argument or a reasoning really does follow from its premises or not? Is there the only one criterion, or are there many criteria? If there are many criteria, what are the intrinsic differences between them? It is logic that deals with the validity of argument and reasoning in general.

A ***logically valid reasoning*** is a reasoning such that its arguments are justified based on some ***logical validity criterion*** provided by a logic system in order to obtain correct conclusions (Note that here the term "correct" does not necessarily mean "true."). Today, there are so many different logic systems motivated by various philosophical considerations. As a result, a reasoning may be valid on one logical validity criterion but invalid on another. For example, the ***classical account of validity***, which is one of fundamental principles and assumptions underlying classical mathematical logic and its various conservative extensions, is defined in terms of ***truth-preservation*** (in some certain sense of truth). It requires that an argument is valid if and only if it is impossible for all its premises to be true while its conclusion is false. Therefore, a classically valid reasoning must be ***truth-preserving***. In general, for a deductive reasoning to be valid, it must be truth-preserving. On the other hand, for any correct argument in scientific reasoning as well as our everyday reasoning, its premises must somehow be ***relevant*** to its conclusion, and vice versa. The ***relevant account of validity*** is defined in terms of ***relevance***. It requires that for an argument to be valid there must be some connection of meaning, i.e., some relevance, between its premises and its conclusion, among other things. Obviously, the relevance between the premises and conclusion of an argument is not accounted for by the classical logical validity criterion, and therefore, a classically valid reasoning is not necessarily relevant.

Proving is the process of finding a justification for an explicitly specified statement from given premises, which are already known facts or previously assumed hypotheses. A ***proof*** is a description of a found justification. A ***logically valid proving*** is a proving such that it is justified based on some logical validity criterion provided by a logic system in order to obtain a correct proof. The most intrinsic difference between reasoning and proving is that the former is intrinsically prescriptive and predictive while the latter is intrinsically descriptive and non-predictive. The purpose of reasoning is to find some new conclusion previously unknown or unrecognized, while the purpose of proving is to find a justification for some specified statement previously given. Proving has an explicitly given target as its goal while reasoning does not. Unfortunately, until now, many studies in Computer Science and Artificial Intelligence disciplines still confuse proving with reasoning.

Prediction is the process to make some future event known in advance, especially on the basis of special knowledge. For any prediction, both the predicted thing and its truth must be unknown before the completion of prediction process. Since reasoning is the only way to draw new conclusions from given premises, there is no prediction process that does not invoke reasoning.

It is obvious that the anticipatory reasoning engine ARE in an ARRS must invoke reasoning rather then proving.

In logic, a sentence in the form of "if ... then ..." is usually called a ***conditional proposition*** or simply ***conditional*** which states that there exists a relation of sufficient condition between the "if" part and the "then" part of the sentence. In general, a conditional must concern two parts which are connected by the connective "if ... then ... " and called the ***antecedent*** and the ***consequent*** of that conditional, respectively. The truth of a conditional depends not only on the truth of its antecedent and consequent but also more essentially on a necessarily relevant and conditional relation between them. The notion of conditional plays the most essential role in reasoning because any reasoning form must invoke it, and therefore, it is historically always the most important subject studied in logic and is regarded as the heart of logic [1].

When we study and use logic, the notion of conditional may appear in both the ***object logic*** (i.e., the logic we are studying) and the ***meta-logic*** (i.e., the logic we are using to study the object logic). In the object logic, there usually is a connective in its formal language to represent the notion of conditional, and the notion of conditional is also usually used for representing a logical consequence relation in its proof theory or model theory. On the other hand, in the meta-logic, the notion of conditional, usually in the form of natural language, is used for defining various meta-notions and describing various meta-theorems about the object logic.

From the viewpoint of object logic, there are two classes of conditionals. One class is empirical conditionals and the other class is logical conditionals. For a logic, a conditional is called an ***empirical conditional*** of the logic if its truth-value, in the sense of that logic, depends on the contents of its antecedent and consequent and therefore cannot be determined only by its abstract form (i.e., from the viewpoint of that logic, the relevant relation between the antecedent and the consequent of that conditional is regarded to be empirical); a conditional is called **a *logical conditional*** of the logic if its truth-value, in the sense of that logic, depends only on its abstract form but not on the contents of its antecedent and consequent, and therefore, it is considered to be universally true or false (i.e., from the viewpoint of that logic, the relevant relation between the antecedent and the consequent of that conditional is regarded to be logical). A logical conditional that is considered to be universally true, in the sense of that logic, is also called an ***entailment*** of that logic. Indeed, the most intrinsic difference between various different logic systems is to regard what class of conditionals as entailments, as Diaz pointed out: "The problem in modern logic can best be put as follows: can we give an explanation of those conditionals that represent an entailment relation?" [10]

The logic system underlying anticipatory reasoning adequately must satisfy the following at least three essential requirements: First, as a general logical criterion for validity of reasoning rather than proving, the logic must be able to underlie relevant reasoning as well as truth-preserving reasoning in the sense of conditional. This is in particular intrinsically important to anticipatory reasoning for prediction, because almost all, if not all, predictions have the representation form of conditional. Second, the logic must be able to underlie paracomplete and paraconsistent reasoning, because in any application area in the real world the completeness and the consistency are often not necessarily guaranteed. In particular, the principle of Explosion that everything follows from a contradiction cannot be accepted by the logic as a valid principle. Third, the logic must be able to underlie temporal reasoning, because anticipatory reasoning for prediction itself is an intrinsically time-dependent reasoning mode.

However, classical mathematical logic and its various classical conservative extensions cannot satisfy any of the above three requirements [1, 2, 3, 7, 8]; traditional (weak) relevant logics can satisfy the first requirement partly and the second requirement but cannot satisfy the third requirement [1, 2, 3, 7, 8]; strong relevant (relevance) logics proposed by the present author can satisfy the first and the second requirements but cannot satisfy the third requirement [3, 7, 8]. The only hopeful candidate which can satisfy the above all three requirements is temporal relevant logic proposed by the present author.

Here we give an axiomatic presentation of various propositional temporal relevant logics. The logical connectives, temporal operators, axiom schemata, and inference rules of temporal relevant logics are as follows:

Primitive logical connectives :

$\Rightarrow$: entailment

$\neg$: negation

$\wedge$: extensional conjunction

Defined logical connectives :

$\otimes$: intensional conjunction, $A \otimes B =_{df} \neg(A \Rightarrow \neg B)$

$\oplus$: intensional disjunction, $A \oplus B =_{df} \neg A \Rightarrow B$

$\Leftrightarrow$: intensional equivalence, $A \Leftrightarrow B =_{df} (A \Rightarrow B) \otimes (B \Rightarrow A)$

$\vee$: extensional disjunction, $A \vee B =_{df} \neg(\neg A \wedge \neg B)$

$\rightarrow$: material implication, $A \rightarrow B =_{df} \neg(A \wedge \neg B)$ or

$A \rightarrow B =_{df} \neg A \vee B$

$\leftrightarrow$: extensional equivalence, $A \leftrightarrow B =_{df} (A \rightarrow B) \wedge (B \rightarrow A)$

Temporal operators :

G : future-tense always or henceforth operator,
*G*A means "It will always be the case in the future from now that A"

H : past-tense always operator,

*H*A means "It has always been the case in the past up to now that A"

F : future-tense sometime or eventually operator, *F*A means "It will be the case at least once in the future from now that A"

P : past-tense sometime operator, *P*B means "It has been the case at least once in the past up to now that A"

These temporal operators are not independent and can be defined as follows: *G*A $=_{df}$ ¬*F*¬A, *H*A $=_{df}$ ¬*P*¬A, *F*A $=_{df}$ ¬*G*¬A, and *P*A $=_{df}$ ¬*H*¬A.

Axiom schemata :

E1 A⇒A
E2 (A⇒B)⇒((C⇒A)⇒(C⇒B))
E2′ (A⇒B)⇒((B⇒C)⇒(A⇒C))
E3 (A⇒(A⇒B))⇒(A⇒B)
E3′ (A⇒(B⇒C))⇒((A⇒B)⇒(A⇒C))
E3″ (A⇒B)⇒((A⇒(B⇒C))⇒(A⇒C))
E4 (A⇒((B⇒C)⇒D))⇒((B⇒C)⇒(A⇒D))
E4′ (A⇒B)⇒(((A⇒B)⇒C)⇒C)
E4″ ((A⇒A)⇒B)⇒B
E4‴ (A⇒B)⇒((B⇒C)⇒(((A⇒C)⇒D)⇒D))
E5 (A⇒(B⇒C))⇒(B⇒(A⇒C))
E5′ A⇒((A⇒B)⇒B)

N1 (A⇒(¬A))⇒(¬A)
N2 (A⇒(¬B))⇒(B⇒(¬A))
N3 (¬(¬A))⇒A

C1 (A∧B)⇒A
C2 (A∧B)⇒B
C3 ((A⇒B)∧(A⇒C))⇒(A⇒(B∧C))
C4 (LA∧LB)⇒L(A∧B), where LA $=_{df}$ (A⇒A)⇒A

D1 A⇒(A∨B)
D2 B⇒(A∨B)
D3 ((A⇒C)∧(B⇒C))⇒((A∨B)⇒C)

DCD (A∧(B∨C))⇒((A∧B)∨C)

C5 (A∧A)⇒A
C6 (A∧B)⇒(B∧A)
C7 ((A⇒B)∧(B⇒C))⇒(A⇒C)
C8 (A∧(A⇒B))⇒B
C9 ¬(A∧¬A)
C10 A⇒(B⇒(A∧B))

T1 *G*(A⇒B)⇒(*G*A⇒*G*B)
T2 *H*(A⇒B)⇒(*H*A⇒*H*B)
T3 A⇒*G*(*P*A)
T4 A⇒*H*(*F*A)
T5 *G*A⇒*G*(*G*A)
T6 (*F*A∧*F*B)⇒*F*(A∧*F*B)∨*F*(A∧B)∨*F*(*F*A∧B)
T7 (*P*A∧*P*B)⇒*P*(A∧*P*B)∨*P*(A∧B)∨*P*(*P*A∧B)
T8 *G*A⇒*F*A
T9 *H*A⇒*P*A
T10 *F*A⇒*F*(*F*A)
T11 (A∧*H*A)⇒*F*(*H*A)
T12 (A∧*G*A)⇒*P*(*G*A)

Inference rules :

⇒E : "from A and A⇒B to infer B" (Modus Ponens)
∧I : "from A and B to infer A∧B" (Adjunction)
TG : "from A to infer *G*A and *H*A" (Temporal Generalization)

Thus, various relevant logic systems may now defined as follows, where we use "A | B" to denote any choice of one from two axiom schemata A and B.

$\mathbf{T}_{\Rightarrow}$ = {E1, E2, E2′, E3 | E3″} + ⇒E
$\mathbf{E}_{\Rightarrow}$ = {E1, E2 | E2′, E3 | E3′, E4 | E4′} + ⇒E
$\mathbf{E}_{\Rightarrow}$ = {E2′, E3, E4″} + ⇒E
$\mathbf{E}_{\Rightarrow}$ = {E1, E3, E4‴} + ⇒E
$\mathbf{R}_{\Rightarrow}$ = {E1, E2 | E2′, E3 | E3′, E5 | E5′} + ⇒E

$\mathbf{T}_{\Rightarrow,\neg} = \mathbf{T}_{\Rightarrow}$ + {N1, N2, N3}
$\mathbf{E}_{\Rightarrow,\neg} = \mathbf{E}_{\Rightarrow}$ + {N1, N2, N3}
$\mathbf{R}_{\Rightarrow,\neg} = \mathbf{R}_{\Rightarrow}$ + {N2, N3}

$\mathbf{T} = \mathbf{T}_{\Rightarrow,\neg}$ + {C1~C3, D1~D3, DCD} + ∧I
$\mathbf{E} = \mathbf{E}_{\Rightarrow,\neg}$ + {C1~C4, D1~D3, DCD} + ∧I
$\mathbf{R} = \mathbf{R}_{\Rightarrow,\neg}$ + {C1~C3, D1~D3, DCD} + ∧I

$\mathbf{Tc} = \mathbf{T}_{\Rightarrow,\neg}$ + {C3, C5~C10}
$\mathbf{Ec} = \mathbf{E}_{\Rightarrow,\neg}$ + {C3~C10}
$\mathbf{Rc} = \mathbf{R}_{\Rightarrow,\neg}$ + {C3, C5~C10}

Here, $\mathbf{T}_{\Rightarrow}$, $\mathbf{E}_{\Rightarrow}$, and $\mathbf{R}_{\Rightarrow}$ are the purely implicational fragments of **T**, **E**, and **R**, respectively, and the relationship between $\mathbf{E}_{\Rightarrow}$ and $\mathbf{R}_{\Rightarrow}$ is known as $\mathbf{R}_{\Rightarrow} = \mathbf{E}_{\Rightarrow}$ + A⇒LA; $\mathbf{T}_{\Rightarrow,\neg}$, $\mathbf{E}_{\Rightarrow,\neg}$, and $\mathbf{R}_{\Rightarrow,\neg}$ are the implication-negation fragments of **T**, **E**, and **R**, respectively; **Tc**, **Ec**, and **Rc** are strong relevant (relevance) logics proposed by the present author.

We can now obtain some minimal or weakest temporal relevant logics as follows:

$\mathbf{T_0T} = \mathbf{T}$ + {T1~T4} + TG
$\mathbf{T_0Tc} = \mathbf{Tc}$ + {T1~T4} + TG
$\mathbf{T_0E} = \mathbf{E}$ + {T1~T4} + TG
$\mathbf{T_0Ec} = \mathbf{Ec}$ + {T1~T4} + TG
$\mathbf{T_0R} = \mathbf{R}$ + {T1~T4} + TG
$\mathbf{T_0Rc} = \mathbf{Rc}$ + {T1~T4} + TG

Note that the minimal or weakest temporal classical logic $\mathbf{K_t}$ = all axiom schemata for **CML** + →E + {T1~T4} +

TG. Other characteristic axiom schemata such as T5 ~ T12 that correspond to various assumptions about time can be added to $\mathbf{T_0T}$, $\mathbf{T_0Tc}$, $\mathbf{T_0E}$, $\mathbf{T_0Ec}$, $\mathbf{T_0R}$, and $\mathbf{T_0Rc}$ respectively to obtain various temporal relevant logics. These logics can be extended into various first-order predicate logics by adding various symbols of quantifiers, individual variables, individual constants, individual functions, and individual predicates into their formal (object) languages, and introducing those usual axiom schemata and inference rules relative to quantifiers.

Temporal relevant logic provides for the prediction model PM of an ARRS with a formal language to represent knowledge about the reactive system RS, its application area, and its external computing environment, and also provides for the anticipatory reasoning engine ARE with a logical validity criterion to reason out valid predictions.

4. Implementation Problems

A sound logical basis only provides for an ARRS with a fundamental theory for knowledge representation and reasoning. There are many application-dependent implementation problems we have to solve in order to construct a really useful ARRS.

First, the prediction model PM of an ARRS must represent an exact model for RS and its external computing environment. Second, the reactive system RS must be able to get sufficient information from its external computing environment. Third, the anticipatory reasoning engine ARE must be able to reason out predictions effectively and efficiently in time for taking anticipatory actions. We are designing an anticipatory reasoning engine based on EnCal, an automated forward deduction system for general-purpose entailment calculus [4]. Finally, according to predictions, how to effectively decide which anticipatory actions have to be taken and how to take the actions efficiently is an important problem to the usefulness of an ARRS.

5. Possible Applications

An ARRS may be useful in any application where taking the anticipation according to predictions by anticipatory reasoning is to be desired. Some possible applications of ARRSs are as follows: information security engineering, highly reliable systems, highly secure systems, real-time control systems, defense systems, decision support systems, strategic planning systems, self-organization systems, adaptive systems, futures marketing systems, securities marketing systems, and computer and network game systems.

An ARRS may also be useful, if it takes spatial reasoning into account, in those applications such as robotics, spatial and temporal database systems, and GISs where it is to be desired to take the anticipation according to predictions about some things, which are not only time-dependent but also space-dependent, by anticipatory reasoning.

6. Concluding Remarks

We have presented the background and motivation to develop anticipatory reasoning-reacting systems, proposed the architecture and logical basis of the systems, and shown their implementation problems and possible applications. Although there are many challenging theoretical and technical problems, we have pioneered a new direction on the design and development of highly reliable and highly secure reactive systems.

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