Robot Self-Awareness: Temporal Relation Based Data Mining

Anna Gorbenko, Vladimir Popov, Andrey Sheka

***Abstract*—A self-aware system has the possibility of dealing with novel situations more effectively than a system without self-awareness, because it would have the capacity for introspection that would allow it to inspect and exploit its representations. A self-aware system can attend to its own internal states, thus providing a means of generating introspection and self-modification capabilities. In this paper we consider robot self-awareness from the point of view of temporal relation based data mining. In particular, we consider the problem of learning effects of mobile robot actions and self-detection. This paper describes a new method for representing and reasoning about temporal knowledge. In particular, this paper describes a new method for maintaining the relationships between temporal intervals.**

***Index Terms*—self-awareness, self-detection, temporal relation, mobile robot.**

I. Introduction

MANY of current artificial intelligence systems, including robotic systems, are unacceptably brittle in the face of change (e.g. [1]). Respectively, in many cases, system designers and developers must explicitly specify all actions and behaviors in order for the system to work as intended such that it achieves its design goals. In dynamic and open complex environments it becomes difficult for systems developers to specify specific behaviors and actions for all possible conditions and situations. Typically, software development approaches to structured and well defined problems do not scale in complex and dynamic environments because there is a huge, possibly infinite, number of possibilities that need to be catered for. It is unreasonable to expect that system developers can foresee and develop appropriate responses for all relevant eventualities. Respectively, once deployed, systems are effectively limited by a static set of instructions that encode their designers understanding, conception and perception of the domain in the form of action and behaviors. As a consequence, current systems are limited to domain specific applications where they can perform under a small and finite set of conditions that have been specifically anticipated and represented in a given application. It is not surprising that many of current systems fail to perform in open complex and dynamic environments.

Note that in many different areas robots need to operate in open complex and dynamic environments. They need to adapt to changes of the environment, tasks, etc. For instance, space robotics has been rapidly developed and extensively used. To date, most of space robots are a kind of remote manipulator systems controlled by astronauts. More intelligent system is desirable to reduce the workload and hazardous risk of those astronauts. However, in the space robot operation there are only few features that may assist robots to adapt to changes of the environment (see e.g. [2]). Recent developments in the field of human-robot interaction often associated with problems that require more and more robotic cognition capabilities. However, given the fact that a human has an infinite number of possible interaction capabilities as well as an infinite set of desires and needs, current solutions in the field of robot's cognition look quite poor (see e.g. [3]). Some other examples can be found in [4]–[7].

Even if a robot has no true self-awareness it can have some characteristics of self-awareness, such as having emotional states or the ability to recognize itself in the mirror. Such characteristics can significantly improve efficiency of a robot in open complex and dynamic environments. Also robot self-awareness is a crucial factor in the improvement of human-robot interaction (e.g. [3]).

A self-aware system has the possibility of dealing with novel situations more effectively than a system without self-awareness, because it would have the capacity for introspection that would allow it to inspect and exploit its representations, e.g. internal state. In this paper we consider robot self-awareness from the point of view of temporal relation based data mining. In particular, we consider the problem of learning effects of robot actions and self-detection.

II. Self-Awareness

Robotic systems have been developed to be aware of their own motion [8], able to imitate [9], [10], driven by emotion [11], and able to change their own models of their physical embodiment [12]. Important work in cognitive robotics in reasoning about action and reasoning about knowledge [13]–[15] is relevant.

Often, robots needed in classification of incomplete data by observation (see e.g. [16]). In particular, an important problem for robots is how to distinguish between themselves and the surrounding environment. Robots need to know how to identify which sensory stimuli are produced by their own bodies and which are produced by the external world. Solving this problem is critically important for their normal development.

Self-detection experiments with robots are still quite rare. One of the few published studies on this subject is described in [8]. They implemented an approach to autonomous self-detection similar to the temporal contingency strategy described in [17]. Their robot was successful in identifying movements that were generated by its own body. The robot was also able to identify the movements of its hand reflected in a mirror as self-generated motion because the reflection obeyed the same temporal contingency as the robot's body.

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In that study, the self-detection was performed at the pixel level and the results were not carried over to high-level visual features of the robot's body. Thus, there was no permanent trace of which visual features constitute the robot's body. Because of this, the detection could only be performed when the robot was moving. This limitation was removed in a subsequent study [18], which used probabilistic methods that incorporate the motion history of the features as well as the motor history of the robot. The new method calculates and uses three dynamic Bayesian models that correspond to three different hypotheses ("self", "animate other", or "inanimate") for what caused the motion of an object. Using this method the robot was also able to identify its image in a mirror as "self". The method was not confused when a person tried to mimic the actions of the robot. The study presented in [19] is similar to the two studies mentioned above. The main difference between [19] and previous work can be summarized as follows. Self-detection is ultimately about finding a causeeffect relationship between the robot's motor commands and perceptible visual changes in the environment. Causal relationships are different from probabilistic relationships which have been used in previous models.

In [8] developed an infant-like humanoid robot called NICO that can recognize its own motion in its visual field, including in a mirror. NICO expects to see motion in its visual field whenever certain motor movements commence after a certain time. It learns this time characteristic through experimentation. It labels motions that appear in the visual field within this learned time frame as its own motion, thus it can distinguish itself from others based on the idea of linking motion to time.

In [9] considered an approach to consciousness is to maintain consistency of cognition and behavior of self and others in order to understand the behavior of self and others. When a system reaches a state where this behavior of self and others is understood, the system is deemed to be conscious. In [9] determined that the imitative behavior is adequate for analyzing consistency in cognition and behavior of self and others. Also in [9] considered four experiments using a robot's imitating actions, including its own actions in a mirror. The result is that the robot passed a mirror test with 70% accuracy [10]. Being conscious in this sense, the robot was able to discriminate itself and others much of the time, however the relationship between consciousness and awareness in this scenario or context is not discussed or clarified.

There are a number approaches to creating artificial emotions systems and systems of emotion recognition (see e.g. [20]–[23]). Such systems are very useful for intelligent agents and robots. In particular, in [11] developed the Intelligent Soft-Arm Control (ISAC) robot that is not self-aware in the sense that it cannot recognize itself in a mirror, but it can deliberate on its emotions based on memory experience. Self-reflection, self-awareness and sense-of-self are represented by a self-agent which consists of a set of agents interacting with memory systems. The emotion that emerges from an activity of experience is learned and stored in memory systems. When an event occurs, emotions activate the episodic memory which in turn activates cognitive control to suppress current behavior and execute required behavior.

Robots have been developed that exhibit an adaptation capability for their own body [12]. These robots can recover from damage or failure that occurs to their body. A robot continuously creates a concept of its own physical structure (self-modeling) and uses this self-model to generate forward locomotion with four legs initially without knowing what its body actually looks like. When the robot's structure changes unexpectedly, it can reform its internal self-model to generate new behaviors to compensate and accommodate these changes. In this case, it remodels the concept of its own physical structure to generate forward locomotion with three legs when one of its legs is removed. This is possible because it has a model of its own physical structure.

In [1] explored robot self-awareness and the role that attention plays in the achievement self-awareness and proposed a new attention based approach to self-awareness. In particular, in [1] provided a new self-modifying framework for developing an attentive robot with self-awareness based on an architecture that supports the ability of a system to focus attention on the representation of internal states. Note that many of current approaches do not focus on directing a robot's attention to its own internal processes. If we add an attention process to a robot so that it can focus on processes that happen internally during self-recognition activities, then we would consider it to be self-aware. What is crucially important is not the ability to recognize itself in a mirror, but rather to be aware of its own internal states. If a robot has totally lost all of its outward facing sensations, it may not be aware of its environment, however it can still be aware of itself.

Regardless of an approach to definition of self-awareness the presence of self-awareness is directly dependent on the ability of the robot to learn effects of its actions. In this paper we consider self-awareness precisely as the ability of the robot to learn effects of its actions.

In general case, robot actions may include walking, sitting on a couch, turning on a lamp, and using the coffeemaker, for instance. To investigate these actions, we need some monitoring model (e.g. [24]). It is easy to see that many of these activities are not instantaneous, but have distinct start and end times. Also, it is clear that there are well-defined relationships between time intervals for different activities. These temporal relations can be represented using Allen's temporal relations [25] and can be used for knowledge and pattern discovery.

In [26] described using temporal inference for robot control. Given a domain theory of an environment written in predicate logic and the event calculus, they use abductive reasoning for tasks like map-making and motion planning. The domain theory is not learned. In [27] association rule learning, a technique from knowledge discovery, has been adapted to find temporal associations. This algorithm works on a database of tuples whose elements are propositions with temporal extent. First associations are learned within the tuples by using standard knowledge discovery algorithms that ignore time, and then temporal relations are learned for each association. Some other recent work finds patterns expressed using Allen's relations. One technique [28], [29] measures the strength of a pattern by its total duration, rather than by counts of open and close events. Associations between patterns are learned using rules whose antecedent and consequent are patterns. The consequent of a rule always temporally follows the antecedent. In [30] presented the fluent-learning algorithm. There, the task was to partition robot experience into episodes. In [31] focused on learning the outcomes of controllers. This application of fluent learning was inspired by previous work that used the MSDD algorithm to learn planning operators [32].

III. Allen's Temporal Relations

Temporal relations can be represented using Allen's temporal relations [25]. Note that investigation [26]–[32] are based on ideas quite similar to [25]. In particular, these investigation have quite similar limitations. Therefore, we consider Allen's temporal relations in detail.

Let $Start(Z)$ be a start time of a general event Z. Respectively, let $End(Z)$ be an end time of a general event Z. Consider two general events X and Y. Following [25] (see also [33]), we consider the following thirteen temporal relations.

1) X Before Y
$$Start(X) < Start(Y);$$
$$End(X) < Start(Y).$$
2) X After Y
$$Start(X) > Start(Y);$$
$$End(Y) < Start(X).$$
3) X During Y
$$Start(X) > Start(Y);$$
$$End(X) < End(Y).$$
4) X Contains Y
$$Start(X) < Start(Y);$$
$$End(X) > End(Y).$$
5) X Overlaps Y
$$Start(X) < Start(Y);$$
$$Start(Y) < End(X);$$
$$End(X) < End(Y).$$
6) X Overlapped-By Y
$$Start(Y) < Start(X);$$
$$Start(X) < End(Y);$$
$$End(Y) < End(X).$$
7) X Meets Y
$$Start(Y) = End(X).$$
8) X Met-by Y
$$Start(X) = End(Y).$$
9) X Starts Y
$$Start(X) = Start(Y);$$
$$End(X) < End(Y).$$
10) X started-by Y
$$Start(X) = Start(Y);$$
$$End(X) > End(Y).$$
11) X Finishes Y
$$Start(X) > start(Y);$$
$$End(X) = End(Y).$$
12) X Finished-by Y
$$Start(X) < Start(Y);$$
$$End(X) = End(Y).$$
13) X Equals Y
$$Start(X) = Start(Y);$$
$$End(X) = End(Y).$$

Note that for many applications Allen's temporal relations are sufficient. In some cases, researchers use only a proper subset of the set of Allen's temporal relations. In particular, in [32] used the following set of relationships:

$SBEB(A, B)$: A starts before B, ends before B; Allen's "overlap".

$SWEB(A, B)$: B starts with A, ends before A; Allen's "starts".

$SAEW(A, B)$: B starts after A, ends with A; Allen's "finishes".

$SAEB(A, B)$: B starts after A, ends before A; Allen's "during".

$SWEW(A, B)$: B starts with A, ends with A; Allen's "equal".

$ES(A, B)$: B starts after A ends; amalgamating Allen's "meets" and "before".

Note, however, that in [32] temporal patterns expressed using fluents. A fluent is a proposition with temporal extent. For example, "drinking-coffee" can be defined as a fluent that is true whenever I am drinking coffee. This fluent can be represented as a binary time series x, where $x[t]$ is 1 if and only if I am drinking coffee at time t (see also [34]). Respectively, temporal relations needed only to express relations of fluents.

In general, Allens temporal relations are not sufficient to fully characterize the relations between events. To analyze limitations of Allens temporal relations and further investigations, we used mobile robot testbed.

IV. Mobile Robot Testbed

For our experiments, we use autonomous mobile robots Kuzma-I (e.g. Figure 1) and Kuzma-II (e.g. Figure 2).

Design of the robot Kuzma-I based on the well-known RC cars. From RC-CAR AT-10ES Thunder Tiger [35] we use only the four wheel chassis, the high torque DC-MOTOR and a steering servo. The DC-MOTOR drives the chassis and a steering servo controls the direction. The electronic system based on SSC-32 microcontroller [36]. Onboard computer based on a motherboard with x86 compatible processor AMD Geode LX600 for embedded systems. The robot is equipped with USB web camera Live! Cam Video IM Pro (VF0410) [37].

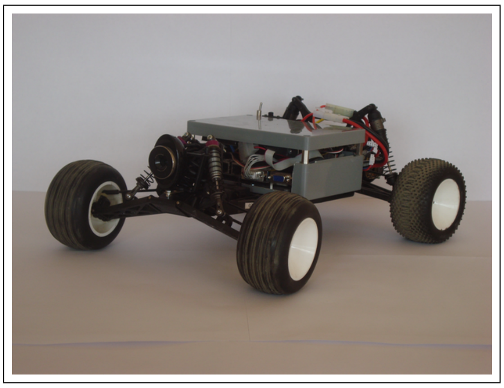

Fig. 1. Robot Kuzma-I.

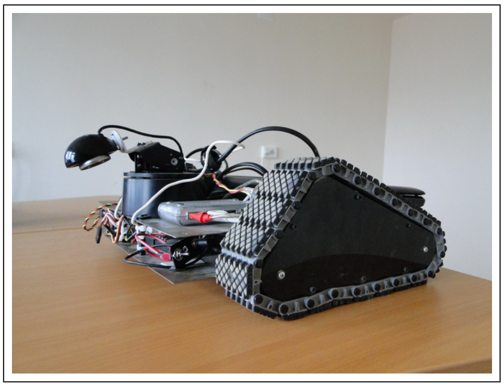

Fig. 2. Robot Kuzma-II. The robot is located on the table. Its mobility is not limited. If in this state motors of the robot will receive a command to rotate, then the robot will move.

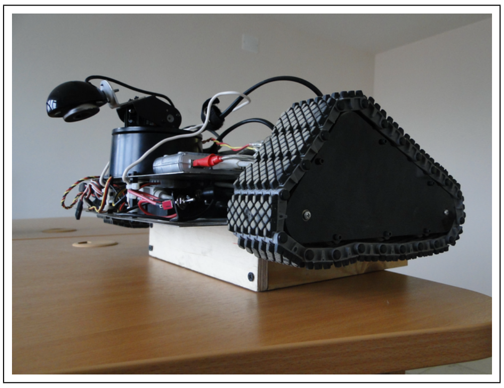

Fig. 3. Suppose that in this state motors of the robot will receive a command to rotate. Since the robot is mounted on a wooden tray, it will remain stationary.

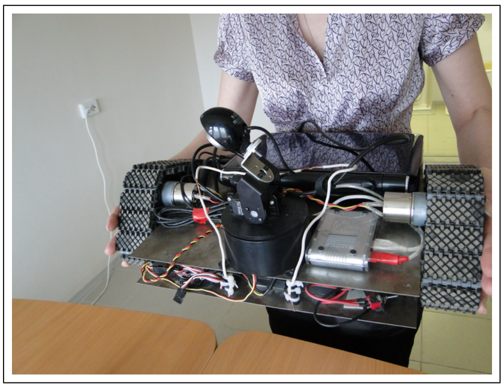

Fig. 4. The robot is in the hands of the researcher. In this state the robot can observe only fingers of the researcher.

Design of the robot Kuzma-II based on the well-known Johnny 5 Robot [38]. By utilizing heavy duty polypropylene and rubber tracks with durable ABS molded sprockets the robot has excellent traction. It includes two 12vdc 50:1 gear head motors [39] and the Sabertooth 2 x 5 R/C motor controller [40]. The body of Johnny 5 Robot wasn't used. The original panels of Johnny 5 Robot were replaced with panels of a large area (30×33 cm) of stainless steel. This allowed us to significantly increase the payload of the robot. Also, it provided a much greater structural strength.

The robot is equipped with one or more batteries Acme-Power UC-5 [41]. Also used a standard laptop battery.

The electronic system based on SSC-32 microcontroller. Onboard computer of this robot is Asus Eee PC 1000HE with OS Windows XP SP2. The robot is equipped with a 2 DOF robotic camera (USB web camera Live! Cam Video IM Pro (VF0410)).

On both robots is running the same control system. The basic robot control system developed in Java. This system is designed to work with devices. Intelligent functions assigned to the advanced robot control system. This system developed using the C# programming language on the .NET 2.0 framework. Both robots use a visual navigation system.

Using a wireless connection both robots have access to resources of a cluster. We use heterogeneous cluster based on three clusters (Cluster USU, Linux, 8 calculation nodes, Intel Pentium IV 2.40GHz processors; umt, Linux, 1664 calculation nodes, Xeon 3.00GHz processors; um64, Linux, 128 calculation nodes, AMD Opteron 2.6GHz bi-processors) [42].

V. Limitations of Allen's Temporal Relations

Allen's temporal relations describe relatively well the dependence of two events. For instance, motors received a command to rotate and the robot moves (e.g. Figure 2).

However, Allen's algebra does not include some important relations. For instance, in a state represented in Figure 2 mobility of the robot is not limited but it located on the table. Motion of the robot may cause a fall.

Of course, the robot can permanently check for threats of falling. However, permanent or even periodic verifications of such threats will lead to significant drop of performance. Moreover, we can consider the state represented in Figure 3.

In case of Figure 3 the robot located on too small elevation. Differences in images of table which were obtained in states of Figure 2 and Figure 3 can not be found using a webcam. The robot does not see a wooden tray. Therefore, the robot can not find the cause of the lack of movement using a direct verification.

In some cases, verification is possible, but it requires considerable efforts because it is necessary to recognize some small items. For instance, in Figure 4 the robot must recognize fingers. Note that the information on the location of the robot relative to the floor can also be used. However, this information describes the state of the robot insufficiently precisely.

In Figure 4 and Figure 5, the robot can determine the fact that it is substantially above the floor. The robot can use this fact to find the cause of the lack of movement. However, in Figure 5 tracks of the robot can move but in Figure 4 tracks

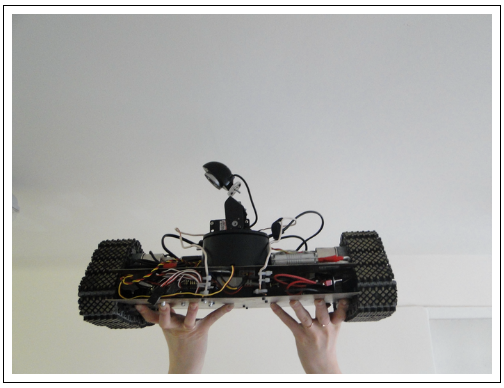

Fig. 5. The researcher took the robot in hands and raised it above her head.

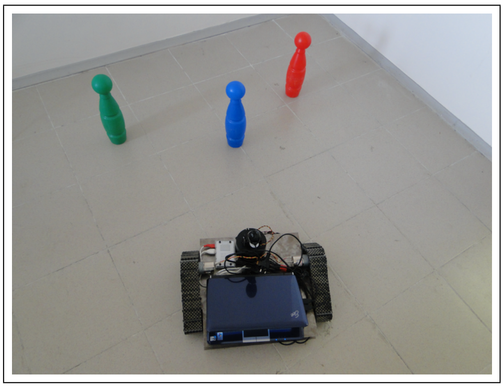

Fig. 6. Kuzma-II uses colored skittles as landmarks.

of the robot can not move. The cause of this can not be found by analyzing relative position of the robot and the floor.

Another possible way for Allen's algebra is to construct a chain of events. However, this also causes significant difficulties. In particular, we may need to introduce some dummy events. Besides, the chain of events may be too long. In particular, in paper [33] considered temporal intervals whose length was 2 days, 33 days, and 66 days. In addition, we should take into account that in the case of mobile robots there are too many events. For instance, our robots use colored skittles as landmarks (e.g. Figure 6). Taking into account that our robots uses only visual navigation, detection (disappearance) of each color skittle is an event that is essential for self-detection. Considering only those events within 66 days we can get a chain which consists from more than 6 millions of such events.

In addition the reconstruction of the chain of events requires consideration of a large number of variants. For instance, we can consider a state represented in Figure 7.

The fact that robots Kuzma-I and Kuzma-II in contact is not sufficient to argue that the cause of Kuzma-II motion is a motion of Kuzma-I. It is possible that the cause of Kuzma-II motion is a researcher's hand (e.g. Figure 8).

In order to detect such possibility we must consider all events for Kuzma-I. The consequence of this is a significant increase in the number of variants. In addition, what to do if a certain event for Kuzma-I and a certain event for Kuzma-II takes the same temporal interval? In general, the number of possible chains grows exponentially on their length.

Note that we can try to use relations “X Before Y” and “X After Y”. However, for instance, in case of Figure

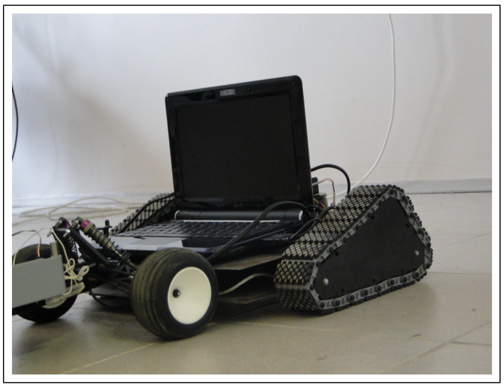

Fig. 7. Robots Kuzma-I and Kuzma-II in contact. If Kuzma-I starts moving forward or Kuzma-II starts moving back, then the second robot will also move.

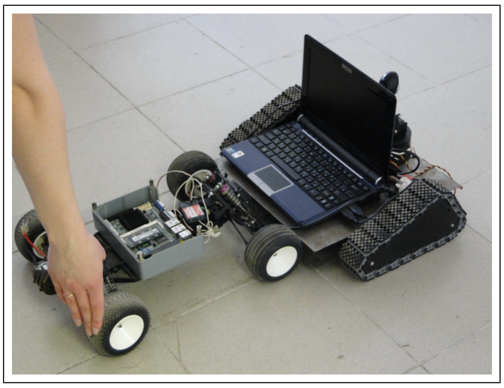

Fig. 8. Kuzma-I, Kuzma-II and a hand of a researcher in contact. Even if a researcher's hand begins to move, it is not necessarily the cause of Kuzma-II motion. Maybe a hand just accompanies motion of Kuzma-I.

2 and Figure 3, these relations do not allow to express directly the fact that the robot is not removed from the table. Respectively, we need to construct a chain of events. A natural way to solve this problem is to consider temporal relations of more than two events. So, the first significant limitation of Allen's temporal relations is the impossibility to simultaneously compare more than two events.

Another significant limitation of Allen's temporal relations is the impossibility to take into account the duration of the event. For example, consider a state which presented in Figure 8. Suppose that a researcher's hand begins to move. Kuzma-I and Kuzma-II are also moving. In particular, we can assume that X = “researcher's hand is moving”; Y = “Kuzma-II is moving”; satisfied temporal relation X Starts Y. We can also suppose that strength and speed of hand movement is uniquely determined by X. However, in this case, since we do not know the duration of X, we can not say with certainty that X is the cause of Kuzma-II motion. Now for the same state suppose that also satisfied temporal relation X During Y. Analyzing each of these relations we may obtain conclusion that none of events is not the cause of the robot motion. Nevertheless, the set of all these events can be the cause of the robot motion. Thus, the third significant limitation of Allen's temporal relations is the impossibility to take into account the number of repetitions of the event.

VI. New Temporal Relations

To avoid limitations of Allen's temporal relations, in this section we consider a new algebra of temporal relations.

At first, consider the set

$$\mathcal{X} = \{x_i \mid x_i \text{ is a fluent, } i \in I\}$$

where I is some index set. Now consider the time series

$$x = (x_1, x_2, \dots, x_{|I|}).$$

Usually, we can assume that there exists some temporal interval which determines boundaries of significance of events. Respectively, we can suppose that there exists some positive integer n such that for any t values of $x_i[s]$, where $s > t+n$ or $s < t-n$, not affect on the awareness of the situation at moment t. Now we can give a new definition of the temporal relation. Any temporal relation can be defined as a time series y such that

$$y = (y_1, y_2, \dots, y_{|I|}),$$

$y_i[s] = 0$ if $x_i[s] = 0$, $y_i[s] = 0$ if $s > t+n$ or $s < t-n$, $y_i[s] \in \{0, 1\}$ if $x_i[s] = 1$ and $t-n \le s \le t+n$ for some t.

It is easy to see that such temporal relations allow us to avoid all the three limitations of Allen's temporal relations which we have considered above. It is easy to verify that Allen's temporal relations form a subset of the set of new temporal relations. Clearly, new temporal relations is relatively easy to use. It is obvious that they inherit all good properties of Allen's temporal relations. However, they have one significant disadvantage. They are too many.

VII. Algebra of Temporal Relations

To reduce the effect of the number of temporal relations on the performance of robot control system can be used various methods of feature selection (e.g. [43]), structuring (e.g. [44]), and unification (e.g. [45]). In our framework, we consider an algebra on the set of temporal relations for feature structuring. Also we use an unification of elementary events.

We can define the algebraic operation $\star$ on the set of temporal relations as follows. Let

$$u \star v = z$$

where $z_i[t] = 1$ if and only if $u_i[t] = 1$ or $v_i[t] = 1$ for all t. Such a definition is quite natural. For arbitrary time series x_i, we can consider $x_i[t]$ as an elementary event. The result of operation takes into account all elementary events that are taken into account by at least one of operands.

Let $\mathcal{R}$ be the set of all temporal relations. Let $R \subseteq \mathcal{R}$. It is easy to check that $\mathcal{S} = \langle R \mid \star \rangle$ is a semigroup for any $R \neq \emptyset$. Now, instead of the set of all temporal relations, we can consider only a set of generators of the semigroup $\mathcal{S}$. Remaining relations we can obtain using operation $\star$. In particular, when used on a robot, we can define semantics only for generators of of the semigroup. Semantics of remaining relations will follow directly from semantics of generators and a decomposition in product. Such approach allows us to use concepts the status and the diameter of the algebra to regulate the ratio between the number of predefined information and the complexity of representation (e.g. [46], [47]).

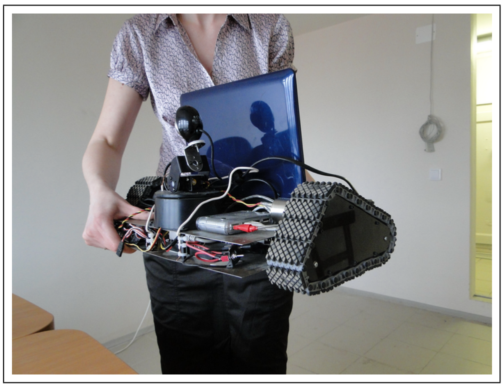

Fig. 9. In this state both webcams of the robot can observe the presence of the researcher. The researcher holds a robots with both hands. If it removes at least one hand, then the robot falls to the floor.

VIII. Unification of Elementary Events

To further reduce the number of temporal relations whose semantics are predetermined, we can use a unification of elementary events.

For example, Kuzma-II equipped with two cameras. Consider the following elementary events:

"The robot is on a table."

"A researcher is near to the robot."

For first camera, we denote these events by u_1 and u_2, respectively. For second camera, we denote these events by v_1 and v_2, respectively. To be sure that one of these events takes place at time t it is enough validity of at least one of the following relations: $u_i[t] = 1$, $v_i[t] = 1$. In particular, in Figure 8 we have $v_2[t] = 1$ and in Figure 9 we have $v_1[t] = v_2[t] = 1$. This situation is quite common. Respectively, often we can use the following operation of unification of elementary events:

$$u * v = 1$$

if and only if $u = 1$ or $v = 1$.

However, in many cases, it is interesting to use another way. For example, for first camera, we consider an elementary event "A researcher holds the robot by right hand." For second camera, we consider an elementary event "A researcher holds the robot by left hand." If we require validity of both relations then we get a new relation that describes a new event "The researcher holds a robots with both hands." Note that this event is not elementary. We can obtain it only by some unification. Even more difficult to express an event "The researcher safely holds a robots with both hands."

IX. Learning Effects of Mobile Robot Actions and Self-Detection

In self-detection the goal of the robot is to classify the set of features into either "self" or "other" (e.g. [19]). The problem of self-detection by a robot is divided into two separate problems as follows:

How can a robot estimate its own efferent-afferent delay, i.e., the delay between the robots motor actions and their perceived effects?

How can a robot use its efferent-afferent delay to classify the visual features that it can detect into either "self" or "other"?

Note that for mobile robots the ability of a robot to estimate its own efferent-afferent delay is a part of the problem which requires to distinguish between their own movement, external sources of movement, and external obstacles to movement. If a robot learns to distinguish between their own movement and external sources, then it can trivially classify the visual features that it can detect into either "self" or "other". Indeed, we can simply use the following principle: *If I move and "something" always moves with me, then "something" is a part of me*. Therefore, for mobile robots the main problem in self-detection is to determine external sources of movement and external obstacles to movement.

To learn effects of robot actions and self-detection we need to establish a correspondence between robot actions and some interesting patterns. For this purpose we can use temporal relations which is discussed above. In the next section, we discuss our approach to mining for interesting patterns.

X. Mining for Interesting Patterns

A common technique used is the discovery of patterns which are frequent and happen often. But using temporal relations to mine, the entire concept of sequence is now represented by temporal relations. Frequency can be the number of times that particular pattern is found, length is the number of elementary events involved in that pattern and the periodicity can be the measure of time span it takes before it repeats itself.

In our investigations, for initial recognition, we use an intelligent system which is based on neural networks and threshold schemes.

The well-known problem of the longest common subsequence is a classical distance measure for strings. In particular, different versions of the longest common subsequence problem frequently used to mine interesting patterns (see e.g. [48]–[52]). In our investigations, we mine interesting patterns using the longest common subsequence technique with maximal consecutive, where we find a long sequence which is a subsequence, or a common subsequence of all sequences in a set of sequences. The reason for performing a maximal consecutive look up is that a three commonly-shared subsequence is of significant interest compared to one sequential subsequence. For instance, we have two strings X and Y, where

$$X = ababcdabb,$$

$$Y = abcdcbb.$$

It is easy to check that

$$X[1]X[2]X[5]X[6]X[8]X[9] =$$
$$X[3]X[4]X[5]X[6]X[8]X[9] =$$
$$abcdbb,$$

where we use $X[i]$ to denote the ith letter in sequence X, is a longest common subsequence of two strings X and Y. It is clear that the sequence

$$X[3]X[4]X[5]X[6]X[8]X[9]$$

is more interesting than the sequence

$$X[1]X[2]X[5]X[6]X[8]X[9].$$

However, this situation is obvious. Now consider the following two sequences:

$$X = aabaabaabaabdddeddddegggggg,$$

$$Y = ggggggfddddfdddcaacaacaacaa.$$

It is easy to check that

$$aaaaaaaa$$

is a longest common subsequence of X and Y. However, it is not obvious that this subsequence gives us the best result. May be, sequences

$$ddddddd$$

and

$$gggggg$$

are better.

We can define a longest common subsequence with maximal consecutive by different ways.

The length of a sequence S is the number of letters in it and is denoted as $|S|$. Given a set of sequences $\mathcal{S} = \{S_i \mid 1 \le i \le m\}$ and the sequence T over some fixed alphabet Σ, the sequence T is a subsequence of some sequence S_i if T can be obtained from S_i by deleting some letters from S_i. The sequence T is a common subsequence of the set of sequences $\mathcal{S}$ if T can be obtained from S_i by deleting some letters from S_i for all i such that $1 \le i \le m$. The sequence T is a longest common subsequence of $\mathcal{S}$ if T is a common subsequence of $\mathcal{S}$ and if U is a common subsequence of $\mathcal{S}$ then $|U| \le |T|$. The sequence $T \in \mathcal{T}$ is a longest common subsequence of $\mathcal{S}$ over the set $\mathcal{T}$ if T is a common subsequence of $\mathcal{S}$ and if $U \in \mathcal{T}$ is a common subsequence of $\mathcal{S}$ then $|U| \le |T|$. In particular, it is clear that a longest common subsequence of $\mathcal{S}$ is a longest common subsequence of $\mathcal{S}$ over the set $\mathcal{T}$ where $\mathcal{T} = \Sigma^*$.

The Longest Common Subsequence Over the Set $\mathcal{T}$ Problem:

Instance: *An alphabet Σ, a set of sequences $\mathcal{S} \subset \Sigma^*$.*

Task: *Find a longest common subsequence of $\mathcal{S}$ over the set $\mathcal{T}$.*

Of interest to consider the following sets. For simplicity, we use $S[i, j]$ to denote the substring of S consisting of the ith letter through the jth letter. The sequence T is a common substring of $\mathcal{S}$ if T is a substring of S_i for all i such that $1 \le i \le m$. The sequence T is a longest common substring of $\mathcal{S}$ if T is a common substring of $\mathcal{S}$ and if U is a common substring of $\mathcal{S}$ then $|U| \le |T|$. Let

$$\mathcal{T}_1 = \{U \mid U \text{ is a common subsequence of } \mathcal{S},$$
$$V \text{ is a substring of } U, \text{ and } V \text{ is a longest}$$
$$\text{common substring of } \mathcal{S}\};$$

$$\mathcal{T}_2 = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ 1 \le i \le m, k \le r\};$$

$$\mathcal{T}_3 = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ |S_i[j_{i,p}, l_{i,p}]| \ge t, 1 \le p \le k, 1 \le i \le m\};$$

$$\mathcal{T}_4 = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ |S_i[j_{i,p}, l_{i,p}]| \ge t, 1 \le p \le k, 1 \le i \le m, k \le r\};$$

$$\mathcal{T}_5 = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, 1 \le i \le m, k \le r\};$$

$$\mathcal{T}_6 = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, |S_i[j_{i,p}, l_{i,p}]| \ge t, 1 \le p \le k, 1 \le i \le m\};$$

$$\mathcal{T}_7 = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, |S_i[j_{i,p}, l_{i,p}]| \ge t, 1 \le p \le k, 1 \le i \le m, k \le r\};$$

$$\mathcal{T}_8 = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, j_{i,s+1} - l_{i,s} \le a, 1 \le s < k, 1 \le i \le m, k \le r\};$$

$$\mathcal{T}_9 = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, j_{i,s+1} - l_{i,s} \le a, 1 \le s < k, |S_i[j_{i,p}, l_{i,p}]| \ge t, \\ 1 \le p \le k, 1 \le i \le m\};$$

$$\mathcal{T}_{10} = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, j_{i,s+1} - l_{i,s} \le a, 1 \le s < k, |S_i[j_{i,p}, l_{i,p}]| \ge t, \\ 1 \le p \le k, 1 \le i \le m, k \le r\};$$

$$\mathcal{T}_{11} = \{U \mid U = S_i[j_{i,1}]S_i[j_{i,2}] \dots S_i[j_{i,k}], \\ S_i[j_{i,1}]S_i[j_{i,2}] \dots S_i[j_{i,k}] \text{ is a subsequence of} \\ S_i, j_{i,s+1} - j_{i,s} \le a, 1 \le s < k, 1 \le i \le m\};$$

$$\mathcal{T}_{12} = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ |S_i[j_{i,p}, l_{i,p}]| \ge t_p, 1 \le p \le k, 1 \le i \le m\};$$

$$\mathcal{T}_{13} = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ |S_i[j_{i,p}, l_{i,p}]| \ge t_p, 1 \le p \le k, 1 \le i \le m, k \le r\};$$

$$\mathcal{T}_{14} = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, |S_i[j_{i,p}, l_{i,p}]| \ge t_p, 1 \le p \le k, 1 \le i \le m\};$$

$$\mathcal{T}_{15} = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, |S_i[j_{i,p}, l_{i,p}]| \ge t_p, 1 \le p \le k, 1 \le i \le m, k \le r\};$$

$$\mathcal{T}_{16} = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, j_{i,s+1} - l_{i,s} \le a, 1 \le s < k, |S_i[j_{i,p}, l_{i,p}]| \ge t_p, \\ 1 \le p \le k, 1 \le i \le m\};$$

$$\mathcal{T}_{17} = \{U \mid U = S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}], \\ S_i[j_{i,1}, l_{i,1}]S_i[j_{i,2}, l_{i,2}] \dots S_i[j_{i,k}, l_{i,k}] \text{ is a subsequence of} \\ S_i, j_{i,s+1} - l_{i,s} \le a, 1 \le s < k, |S_i[j_{i,p}, l_{i,p}]| \ge t_p, \\ 1 \le p \le k, 1 \le i \le m, k \le r\},$$

where $a, r, t_1, t_2, \dots, t_p$, and t are some constants.

We are not trying to determine which of these methods is best in general. We just choose that sequence which best fits robot actions in the present case. To improve performance of computing system is natural to use a genetic algorithm to select a proper method. Also, a genetic algorithm can be used to evolve sets $\mathcal{T}_i$.

Note that the longest common subsequence problem is **NP**-hard for a general case. Therefore, onboard computers of our mobile robots are used only for initial recognition. To mine interesting patterns we use wireless connection to a cluster. To solve **NP**-hard problems we use genetic algorithms.

XI. Conclusion

In this paper we consider robot self-awareness from the point of view of temporal relation based data mining. We consider the problem of learning effects of mobile robot actions and self-detection. In particular, we have proposed an approach to learning effects of mobile robot actions and self-detection which is based on a new system of temporal relations and a new method of mining for interesting patterns.

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